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POWER SUPPLY FAULT TOLERANT RELIABILITY STUDY

McDonnell Aircraft Company

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13. ABSTRACT (Maximum 200 words)

Current MIL-HDBK-217 (Reliability Prediction Electronic Equipment) prediction techniques estimate the inherent power supply reliability assuming purely static conditions. In the "real world", however, transient conditions such as peaks and surges often exist. These prediction techniques also assume that failure rates are directly proportional to the number of parts designed into the equipment. MIL-HDBK-217 procedures penalize more complex designs by predicting a higher system failure rate. Design features to protect against transient conditions are intended to enhance fielded reliability, however, when incorporated into power supply designs, they result in a lower predicted reliability. Eliminating the transient protection circuitry will result in a higher predicted reliability, but in all likelihood, will decrease the fielded reliability.

This study was undertaken to address this dilemma. The three main objectives were:

1) To determine if, and by how much, transient protection features enhance operational reliability.
2) To determine the most significant good design practices for power supplies.
3) To determine the primary modes of failure for various types of power supplies.

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The report documents a comprehensive literature search on transient protection schemes which are utilized in modern power supplies, and the results of a power supply manufacturer survey. Good power supply design practices were identified and categorized from various sources along with a critique of the compatibility between power supply input specifications and the actual transients they are designed to meet. The report documents the primary modes of failure for avionic power supplies along with an analysis of collected field failure data to determine the correlation between various levels of transient protection and field reliability.

Chapter 1 - Transient Protection Schemes and Applications

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Executive Summary

Objective

Current MIL-HDBK-217 (Reliability Prediction of Electronic Equipment) prediction techniques estimate the inherent power supply reliability assuming purely static conditions. In the "real world", however, transient conditions such as peaks and surges often exist. These prediction techniques also assume that failure rates are directly proportional to the number of parts designed into the equipment. MIL-HDBK-217 procedures penalize more complex designs by predicting a higher system failure rate. Design features to protect against transient conditions are intended to enhance fielded reliability, however, when incorporated into power supply designs, they result in a lower predicted reliability. Eliminating the transient protection circuitry will result in a higher predicted reliability, but in all likelihood, will decrease the fielded reliability.

This study was undertaken to address this dilemma. The three main objectives were:

1) To determine if, and by how much, transient protection features enhance operational reliability.
2) To determine the most significant good design practices for power supplies.
3) To determine the primary modes of failure for various types of power supplies.

If proven feasible, the end result of the study would be development of adjustment factors for MIL-HDBK-217 reliability predictions for power supplies incorporating transient protection circuitry. The adjustment factors would permit increasing the predicted reliability based upon the type of transient protection scheme incorporated.

Findings

Although adjustment factors for the overall power supply based on the complexity of transient protection incorporated were not developed, an adjustment factor for the transient protection circuitry based on the relationship between the failure rate of transient protection circuitry and the remaining electronics of the power supply was developed. It was found that the fielded reliability of the transient protection circuitry was 65% better than predicted. Other significant findings are grouped under the main objective headings below:

1) Determine if, and by how much, transient protection features enhance fielded reliability. The following were significant findings:
   a. There was no correlation between the reliability of the power supplies and the level of transient protection. However, correlation between the failure rate of the protection circuity and the remaining circuity was very clear - protection circuitry fails at a lower rate.
   b. Power supplies are less reliable than other types of electronic modules.
   c. More complex power supplies have consistently proven to perform worse than less complex ones.
   d. Radar power supplies were consistently worse than other power supplies.
   e. Trends indicate lower reliability for more complex transient protection approaches.
2) Determine the most significant good design practices for power supplies. The following are the most significant design practices identified:
   a. Most procurement specifications are inadequate in defining the transients power supplies need to be protected against. A complete specification should include the maximum voltage transients, the voltage waveform (which is not often specified), transient source impedance, peak current and transient duration.
   b. Performance expectations of the transient protection must be specified.
   c. Internal transistor snubbing should be required until analysis

and testing verify that it is unnecessary.

d. Qualification and reliability testing should be expanded to include performance verification during transients.

e. Derating and worst case analysis results must be verified by laboratory measurements for certain parameters including in-rush currents and peak voltage and current waveforms present during transistor switching. Analysis should be updated to reflect differences and the design changed to conform to requirements, if necessary.

3) Determine the primary modes of failures for various types of power supplies. The following are the primary failure modes:

   a. Broken wires.
   b. Broken component leads.
   c. Transformer and inductor windings broken at the interface with lead wires.
   d. Mechanical attachment points (which also provide electrical interface) becoming loose causing intermittent electrical discontinuities and poor thermal paths.
   e. Drive transistor failure.

Study Approach

The study spanned nine months, and was subdivided into seven tasks. A brief description of each task follows.

1) The first task was to collect information on the transient protection schemes utilized in modern power supplies. An extensive literature search was performed through our technical library. Forty-two power supply design textbooks, technical papers and component handbooks were digested for this task. A survey distributed to fifty-seven power supply manufacturers requested information on transient protection schemes, failure modes of power supplies, design trade-offs, etc. Chapter 1 summarizes the literature search effort and the survey results. The list of manufacturers who received the survey is included as Appendix A. The actual survey and the conclusions are attached as Appendix B.

2) The second task was to collect information on good power supply design practices. Sources for this information included military handbooks, technical reports from Air Force research facilities, power supply design textbooks, published literature, component manufacturer's application handbooks and power supply design engineers within McDonnell. The information is contained in Chapter 2 and includes the design guideline, the reasons for the guideline and the source of the data.
3) The third task was to select avionics equipment representing a wide range of applications. The chosen equipment would form the basis for the analytical comparison to determine the effectiveness of transient protection schemes in enhancing operational reliability. Initially, this task required selecting twenty pieces of avionics from the Joint Stars platform equipment list that were being used on other airborne platforms. This objective was not met, however, and an alternate equipment list was chosen. Chapter 3 contains further information on the chosen equipment.
4) The fourth task was to collect and analyze the input specifications for the selected power supplies. This effort was necessary as a baseline for the comparison of power supply reliability and to determine what type of transients power supplies are designed to meet, if any. Chapter 4 contains the input specification information collected.
5) The fifth task was to determine the primary failure modes of power supplies. This was to be accomplished by analyzing the "How-Mal" codes obtained from the Air Force and Navy maintenance data system (Air Force 66-1 system and the Navy 3-M system) and by reviewing historical reliability test data. Chapter 5 contains the collected information.
6) The sixth task was to analyze the collected operational field data to determine the impact transient protection has on the selected power supplies. This was done by comparing the operational field failure rates to the predicted failure rates. Numerous comparisons were made in an attempt to find some correlation between the transient protection schemes and achieved reliability. Chapter 6 contains the detailed information for this part of the effort.
7) The seventh and final task was to establish MIL-HDBK-217 adjustment

factors with respect to power supplies based on previous analyses conducted in the first six tasks. Chapter 7 contains conclusions and recommendations derived from this study.

Acronym List

A	Ampere
AC	Alternating Current
AFB	Air Force Base
APB	Avioncis Planning Baseline
CPS	Computer Power Supply
CR	Clamping Ratio
DC	Direct Current
DIP	Dual Inline Package
di/dt	Current change with respect to time
dv/dt	Voltage change with respect to time
EMI	Electro Magnetic Interference
EMP	Electro Magnetic Pulse
ESD	Electro Static Discharge
FET	Field Effect Transistor
FR	Failure Rate
GCS	Gate Controlled Switch
GDT	Gas Discharge Tube
GTO	Gate Turn Off
HSD	Horizontal Situation Display
I	Current
Ic	Collector Current
IEEE	Institute of Electrical and Electronic Engineers
INS	Inertial Navigation Set
k	kilo
kV	kilo-volt
L	Inductance in Henrys
LRU	Line Replaceable Unit (same as WRA)
MCAIR	McDonnell Aircraft Company
MDI	Multipurpose Display Indicator
MOV	Metal Oxide Varistor
n	Relative value of clamping ability
NEMP	Nuclear EMP
PCB	Printed Circuit Board
RADC	Rome Air Development Center
RDT	Reliability Development Test
RF	Radio Frequency
RTDP	Radar Target Data Processor
SOA	Safe Operating Area
SCR	Silicon Controlled Rectifier
SRA	Shop Replaceable Assembly (same as SRU)
SRU	Shop Replaceable Unit (same as SRA)
STR	Switching Thermal Runaway
TSD	Transient Suppression Diode
V	Volt
Vc	Clamped Voltage
Vce	Collector-Emitter Voltage
VI	Volt-Current
Vr	Reverse Standoff Voltage
WRA	Weapon Replaceable Assembly (same as LRU)

Chapter 1

Transient Protection Schemes and Applications

1.0 Introduction

This chapter addresses several issues. Transients are defined and their sources identified. Transient suppression techniques are discussed, devices used in protection schemes are identified and examples of transient suppressor applications are illustrated.

These issues were addressed via two approaches - a literature search and an industry survey. The literature search was conducted at the McDonnell Aircraft Company (MCAIR) library. In an attempt to determine the state-of-the-art practices for power supply design with respect to transient protection which were not yet available in the literature, a questionnaire was distributed to fifty-seven power supply manufacturers. These manufacturers produce both commercial and military power supplies. It was quite unfortunate, however, that only six manufacturers chose to respond. Most either decided they did not have sufficient time to fill out the questionnaire or, by responding, they would be divulging proprietary information about their design. A list of the vendors who received the questionnaire is attached as Appendix A and a copy of the questionnaire with the summarized conclusions of the respondents is attached as Appendix B.

1.1 Transients Defined

An electrical transient is defined as the condition which exists while a circuit is seeking equilibrium following the upset of a steady state condition, the result of stored energy being quickly released into a circuit. Transient voltage and current levels range from totally unpredictable (lightning) to totally predictable (switching of well defined inductive loads). This transient energy can originate from within the circuit itself or be transmitted or coupled into the circuit from an external source.

1.2 Transient Effects

Transients in excess of a few microseconds can damage semiconductor devices. Damage is usually caused by a large reverse voltage across the PN junction causing avalanche conditions to occur at a small area of the junction due to high electrical field concentrations. A device may survive an avalanche condition as long as the current is limited. If the current is not limited, the semiconductor is heated beyond the point where the coefficient of resistivity becomes negative, allowing even higher currents to flow. The semiconductor has now reached the second breakdown region characterized by current instabilities which lead to filamentary (highly concentrated) currents. These current concentrations induce the semiconductor to melt creating low resistance paths. Transients can also cause leakage current on the surface of the passivation, which over time, will create a low resistance path between terminals virtually shorting the junction of the device. Lead wires and circuit traces are subject to thermal melting if the current density becomes too high.

Passive elements, such as resistors or wire, will melt when subjected to current densities beyond their specified ratings. The dielectric in capacitors will break down or puncture if subjected to voltages beyond their specified ratings. The current which flows through the breakdown region will degrade the dielectric such that subsequent breakdowns will occur at lower and lower voltages, finally resulting in a shorted capacitor. The life of insulation also degrades as a function of voltage. See Chapter 2, Figures 31, 32, 33 and Design Guideline #37 for further information on this topic.

1.3 Transient Sources

Internally generated transients result from switching actions which present high rates of voltage or current change (dv/dt or di/dt) at the power supply inputs and from the release of energy stored in the circuit capacitance and inductance. The main source of internally generated transients in power supply circuits is energy stored in inductors which is released when the current is suddenly switched off, either by a switching action or a fault condition. The voltage produced, equal to $-L\, di/dt$, can add to the operating voltage stored in capacitors. The energy stored in an inductor is limited to $1/2Li^2$ and is generally dissipated very rapidly at a high instantaneous power (energy/time).

Prior to energizing a power supply, the input and output filter capacitors are completely discharged. Once energized, very high currents (referred to as in-rush currents) will flow in an attempt to charge the input capacitors. Simultaneously, the regulator will sense the output voltage and, since the output voltage is low, drive the pass transistor on, allowing the high currents to flow through the transistor to charge the output capacitor. Several negative events can take place under these transient conditions. First, rectifier diodes may be overheated. Second, the pass transistor will be subjected to very high currents at a time when the voltage drop across it is at a maximum, creating high power dissipations and junction temperatures. This can lead to transistor failure or degradation. Third, any inductor in series with this large current pulse will store a great deal of energy. When the transistor finally turns off, this energy will be dissipated across the output capacitor and load in the form of a high overshoot voltage with potentially destructive effects.

When a transformer has been switched into a circuit at the peak primary input voltage, the corresponding step input to the primary winding couples with the stray capacitance and inductance of the secondary winding to produce transient secondary voltages. The secondary side can be viewed as a capacitive divider via the interwinding capacitance. A capacitively coupled transient is not dependent on the turns ratio, so the secondary can possibly see a large fraction of the primary voltage as shown in Figure 1 (note, the turns ratio has nothing to do with the coupled energy in this scenario). Deenergizing the transformer initiates the rapid collapse of the transformer's magnetic flux and magnetizing current inducing secondary transients that can exceed ten times the normal secondary voltages as illustrated in Figure 2.

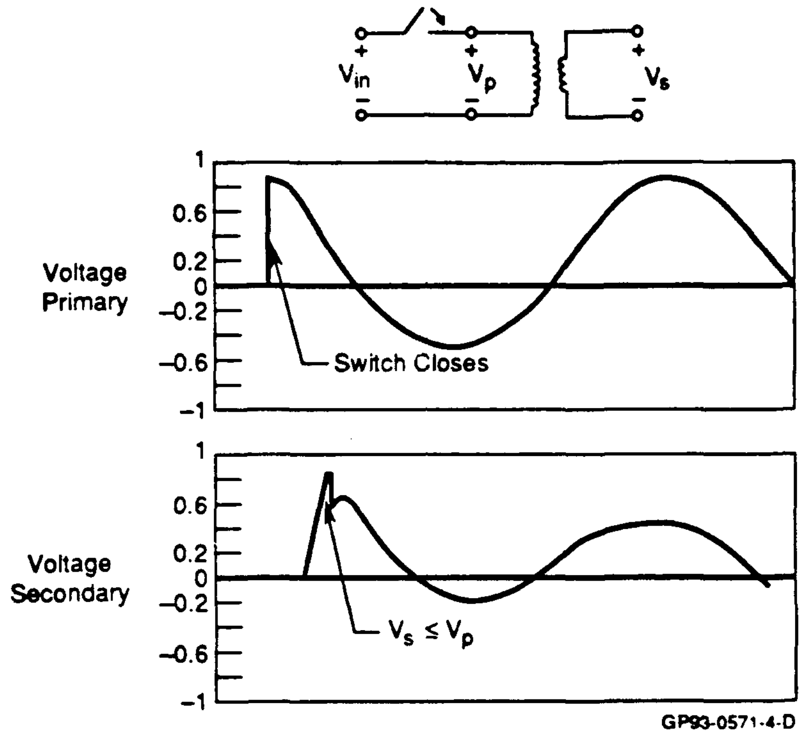

Figure 1. Transformer Coupled Voltage Transient (Turn-on)

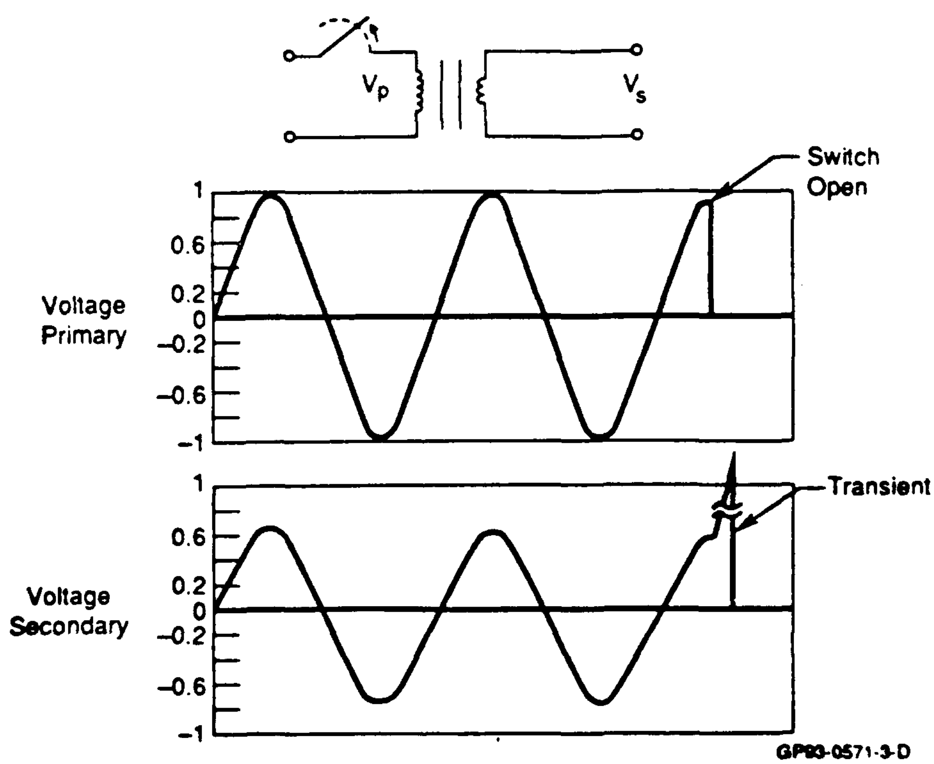

Figure 2. Transformer Coupled Voltage Transient (Turn-off)

External sources of transients include electro-static discharges (ESD), electro-magnetic pulses (EMP), power line transients and lightning. Protecting avionic power supplies from direct lightning strikes is impractical since the strike may contain up to 200k amps of current. However, literature suggests that if one were to design a circuit to withstand peak voltages to 5kV and peak current to 50A (Ref.23), the circuit would be protected from 95% of transients induced by coupling from lightning strikes. IEEE 587, Guide for Surge Voltages in Low Voltage AC Systems, suggests three different waveforms which simulate lightning induced transients for testing electronic circuits. These waveforms represent the Institute of Electrical and Electronic Engineers'(IEEE) analysis of consumer electrical systems, not military aircraft systems. However, in this case, it appears the consumer requirements are more stringent than those of the military, and in lieu of a military standard, it would be better to follow the IEEE standard than none at all.

Figure 3 represents the wave shape the IEEE suggests using with electrical devices used in the "indoor" environment, ie., low current applications. This waveform tests the ability of the transient protection circuitry to respond to a fast rising pulse with the associated nonlinear voltage distributions within the circuit and the ability of semiconductors to handle high dv/dt rates. The oscillating portion tests the ability of the circuitry to handle voltage polarity reversals. For testing high impedance devices, the pulse should be 6kV. For low impedance devices, a 200A pulse is specified. For power supplies that can be subjected to high currents, the IEEE provides two unidirectional pulses as illustrated in Figures 4 and 5. Figure 4 is generally used when testing a device with a high input impedance and Figure 5 is used for devices with a low input impedance. 6kV pulses should be used with Figure 4 for high impedance devices and 3kA pulses used with Figure 5 for low impedance devices. The new version of MIL-STD-461 (Electromagnetic Emission and Susceptibility Requirements for the Control of Electromagnetic Interference) contains two conducted susceptibility tests which are being specified to simulate coupling of a lightning strike into the interface wiring of military avionics. These two tests are referred to as CS10 and CS11. Figure 6 illustrates the waveform the equipment must be able to handle without any degradation of performance or permanent malfunction.

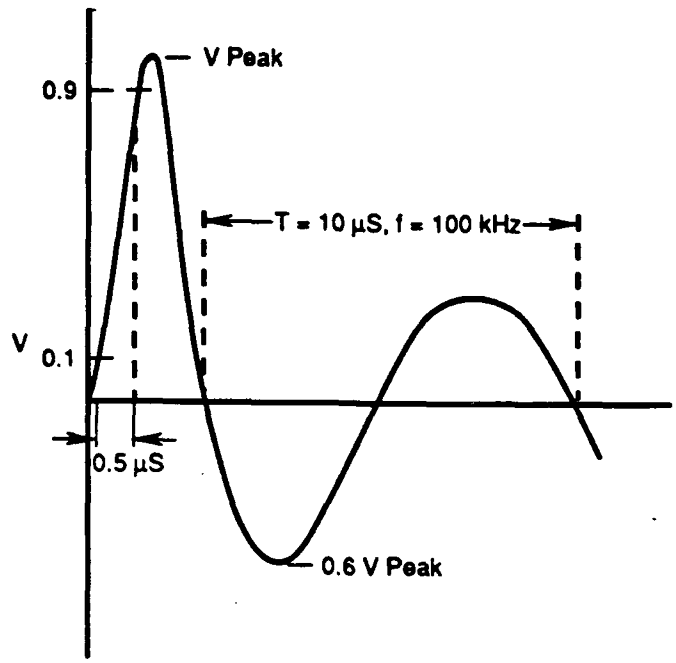

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Figure 3. IEEE Oscillating Voltage Transient

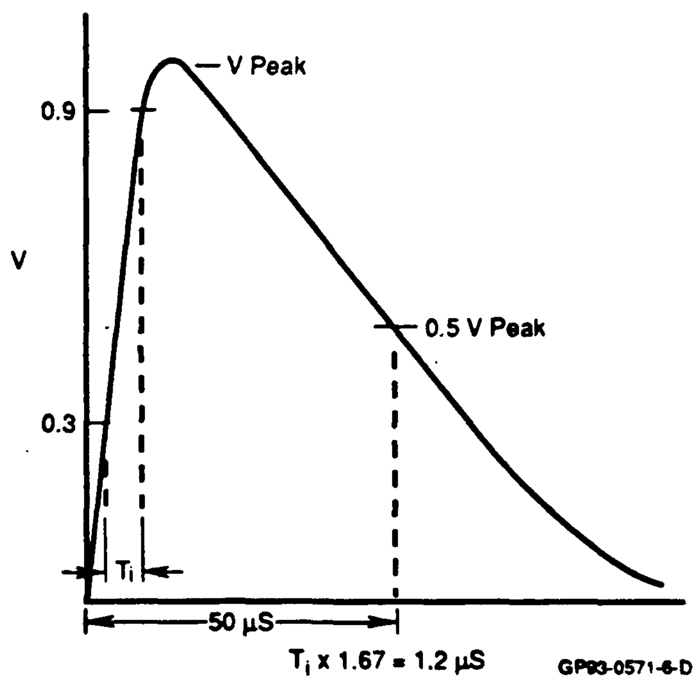

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Figure 4. IEEE Unidirectional Voltage Transient

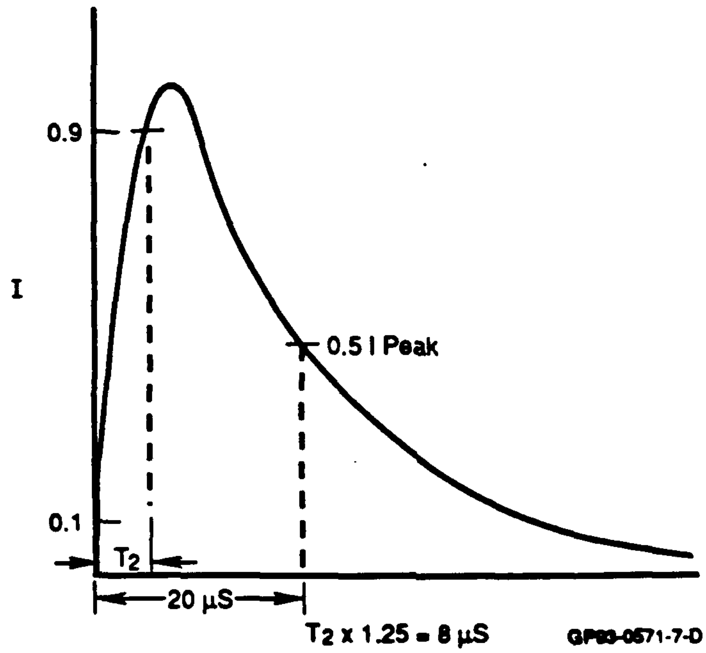

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Figure 5. IEEE Unidirectional Current Transient

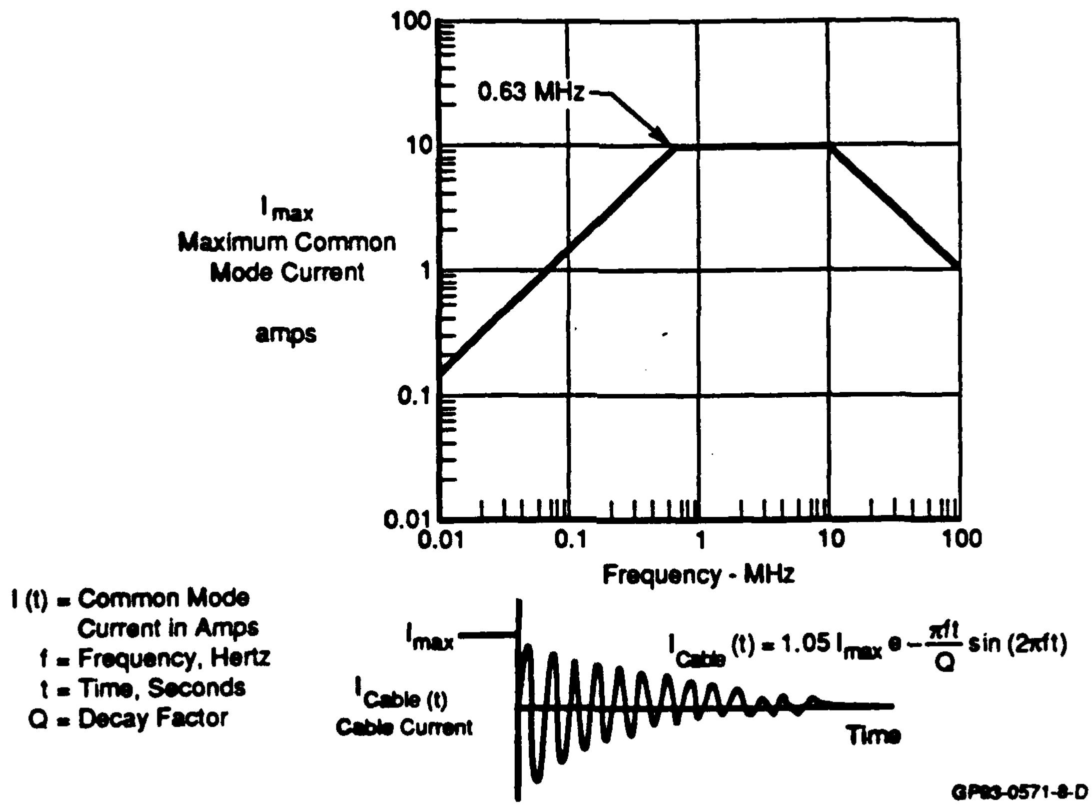

Figure 6. MIL-STD-461 CS10/11 Current Transient

ESD can produce even higher peak voltages of up to 20kV with a dv/dt of 2kV/nanosecond. Fortunately, the current associated with ESD is very small and most electronics at the I/O interface of power supplies are not ESD sensitive.

1.4 Transient Propagation

Once a transient condition is generated, there are two modes of propagation within the circuit: transverse (or normal) mode and common mode. Transverse mode transients are identical to normal signal propagation (the signal is transmitted down one line, through the load and back on the return line). They are generally a result of some switching action within the circuit. A common mode transient is one in which the transient propagates down the signal and return line in the same direction. They are generally caused by lightning strikes (either direct or coupled), nuclear EMP (NEMP) or electro magnetic interference from another source. Common mode transients have no trouble passing through the interwinding capacitance of a transformer since the components of transients are generally high frequency in nature. Similarly, transverse mode transients can be coupled through a transformer and be transformed into a common mode transient on the secondary side allowing the full transient to be present on the secondary side. Figure 7 illustrates a transverse mode transient and Figure 8 illustrates a common mode transient.

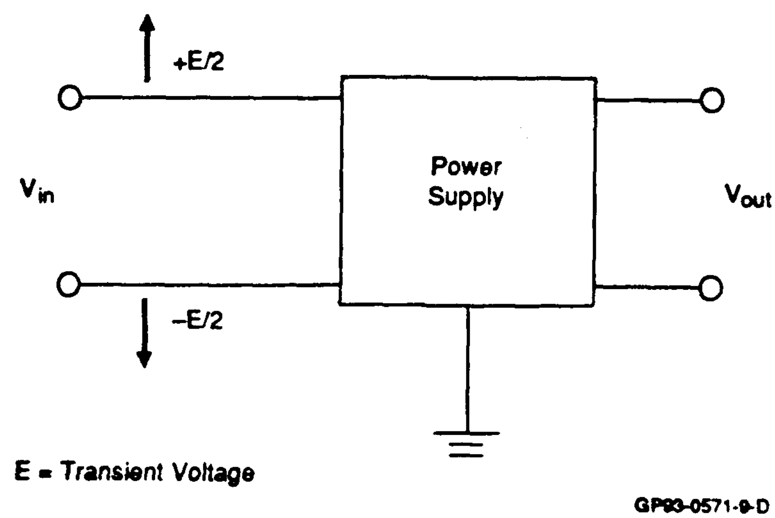

Figure 7. Transverse Mode Transient

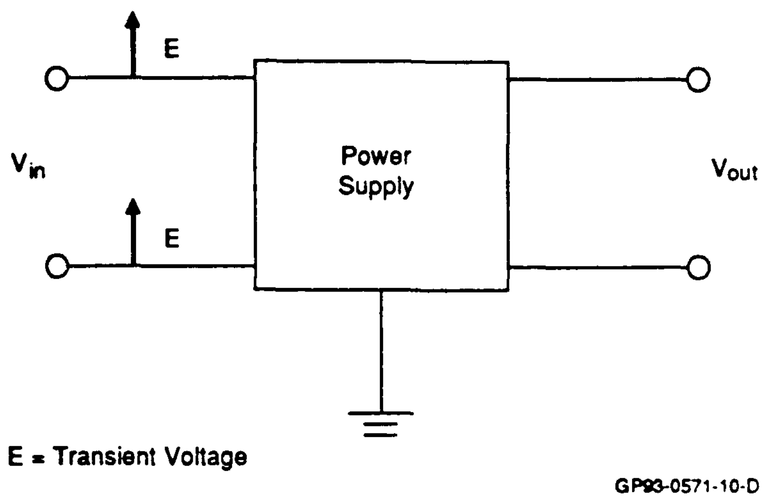

Figure 8. Common Mode Transient

1.5 Transient Suppression Techniques

There are three basic transient suppression techniques: redirect the transient, shut down the power supply or attenuate the transient. A transient can be redirected with voltage clamps and crowbars. Power supplies are generally shut down via the action of a monitor/control device or via the action of a fusing device. Filters, resistors and thermistors are used to attenuate transients.

Voltage clamps are implemented with devices which have nonlinear voltage-current (V-I) characteristics as illustrated in Figure 9. The main advantage of a voltage clamp is that the operating voltage is maintained across the protected device, allowing normal circuit functions to continue. Clamps are connected in parallel with the protected device and are sometimes referred to as passive transient protection. At normal voltage levels, clamps present a high impedance, thus allowing little current to flow while maintaining a large voltage drop (the steady state operating voltage). As the voltage rises above normal operating levels, the turn-on voltage will be reached and the clamps will begin to conduct. Ideally, that voltage level (turn-on voltage) will be maintained (or clamped) while the current flow will rise exponentially and be shunted to ground, thus protecting the circuit and allowing the circuit to remain functional. Clamps will remain conductive until the voltage drops below the turn-on voltage. The main disadvantage of a clamp is that during the clamping period, the clamp will dissipate a considerable amount of power if current levels become excessive. Clamping efficiency depends on the source impedance of the transient since the clamp forms a voltage divider network with the source impedance, ie., the increased current flow causes a large voltage drop across the source impedance. If the source impedance is very small, clamping techniques will not be effective.

Crowbars are implemented with devices which are "switched" from a very high (ideally infinite) impedance to a very low impedance (virtual short) at a given voltage threshold. Crowbars are sometimes referred to as active transient protection due to this switching action. When switched to the low impedance state, the voltage across the circuit to be protected drops very low (0-1 volts) and current flow is shunted to ground producing a V-I characteristic as shown in Figure 10. Since the resulting voltage across the circuit is so low, the circuit becomes non-functional, a major disadvantage of crowbars. Another disadvantage of a crowbar is the current which flows after the device begins to conduct can be very high. Referred to as the follow-on current, this current generally will not damage the crowbar device since the dissipated power is so low, but it can cause damage to other components through which the transient current is flowing. Also, since the follow-on current is maintained at a voltage much lower than normal operating voltages, the circuit continues to not function. To stop the follow-on current, the voltage must be lowered below the holding current, thus resetting the crowbar.

Power supplies can be shut down by removing the base drive from the drive transistors or by a fusing device, the primary methods of handling an over-current condition. Over-current protection is intended to protect the power supply from the effects of shorted outputs by shutting down the power supply. Shorted outputs can be manifested by conducting crowbar devices, the load failing short, the transmission line shorting or through careless maintenance practices. Short circuits cause high current levels to flow which will not be detectable by an overvoltage sensor. Over-current

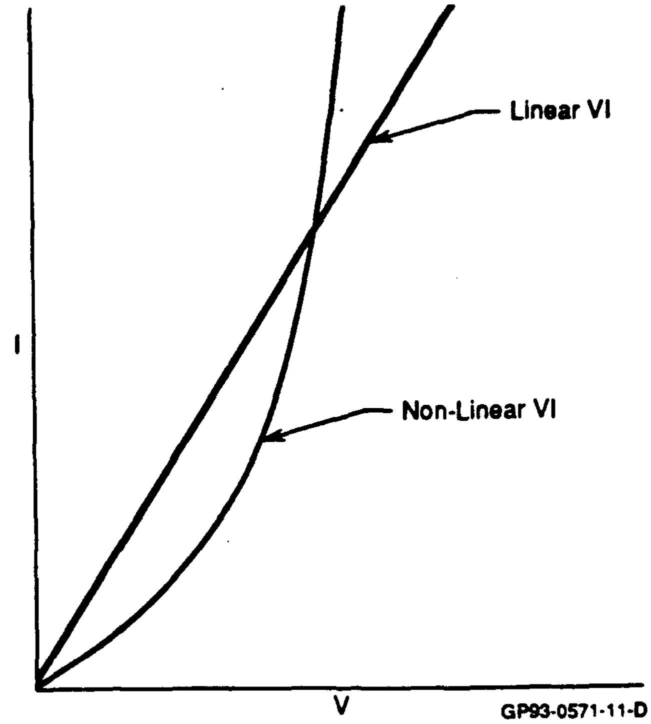

Figure 9. Linear and Nonlinear Volt - Current Characteristics

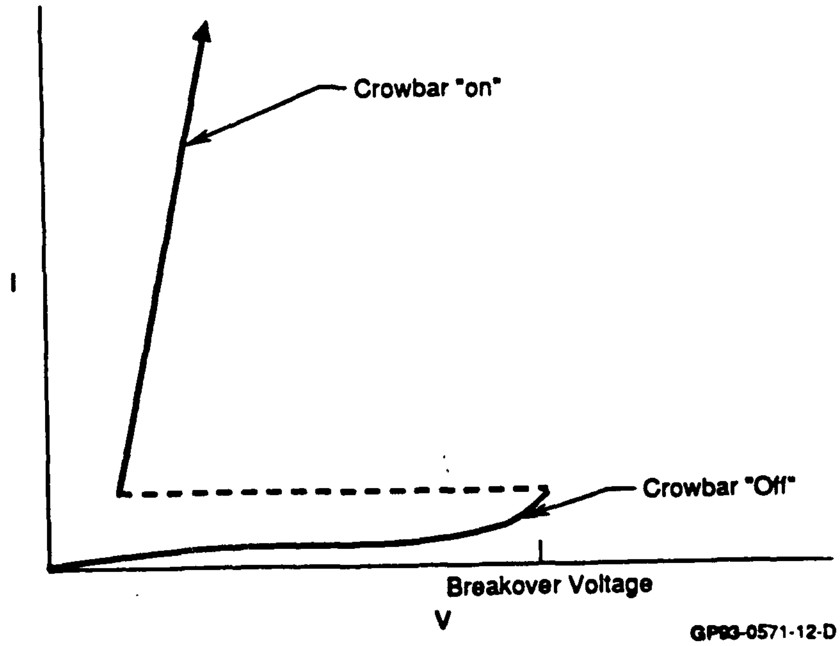

Figure 10. Crowbar V-I Characteristic

situations are sensed by current sensing transformers or voltage divider networks. The output of these devices is fed to voltage comparators with a reference voltage as the other input. Excessive current provides an output signal which will trip the comparator. The comparator outputs a signal which can be used to shut down the supply. Fusing devices such as circuit breakers or fuses can be used, but their response time is slow compared to other techniques and some type of human action is generally necessary to restore power to the circuit, ie. resetting a circuit breaker or replacing a fuse, an undesirable situation.

Filters are used to attenuate transients. Since most transients are high frequency in nature, a low pass filter is generally effective. Drawbacks include self induced resonance with other active components in the circuit and high in-rush currents during turn-on. Resistors, thermistors and inductors can be used to limit the in-rush current, but they reduce the efficiency of the power supply under normal operating conditions.

1.6 Transient Suppression Devices

A good transient suppressor should possess the following characteristics:

1) No leakage current (standby power consumption).
2) High surge energy absorption capabilities.
3) No characteristic change/drift with time.
4) Instant response.
5) No follow-on current.
6) Be inexpensive and reliable.
7) A clamping ratio equal to one.

Items 1-6 are self explanatory. Item 7, the clamping ratio (CR), is a figure of merit for transient suppressors. It is defined as the clamped voltage (Vc) at some specified pulsed current condition divided by the stand-off voltage (Vr). The Vc is the voltage across the device at a specified transient current condition. The Vr is the voltage at which the suppressor first begins to conduct or bypass current. An ideal clamp would have a CR=1, ie., the clamped voltage equals the stand-off voltage regardless of the current flowing through the device, thus allowing the circuit to remain functional and not subjecting the protected components to voltage levels exceeding the standoff voltage. In order for a transient protection device to have a CR equal to one, the V-I relationship must be highly nonlinear. This is represented by the equation $I = KV^n$ where I is the current, V is the voltage, K is a constant dependent on the ratings of the device and n is equal to some value representative of the class of device and the degree of non-linearity with respect to the V-I characteristic. Figure 11 illustrates the effect various values of n have on the V-I characteristic. Precise values of the V-I relationship for a device should be obtained from the manufacturing specifications. On the graph, a vertical plot (high value of n) is equivalent to a CR equal to one. If the CR is greater than one, the voltage across the load will be greater than the standoff voltage. If the CR is less than one, the voltage across the load will be less than the standoff voltage.

There is one negative aspect to having a high value of n. As mentioned in the previous paragraph, high values of n are necessary to clamp voltages at a given value (CR=1). However, devices with a high value of n turn on much quicker than devices with a low n. If a supply has poorly regulated (within tolerances) inputs or outputs, the high n devices will be turning on and dissipating more power during normal steady state operations than devices with low values of n. This is illustrated in Figure 12.

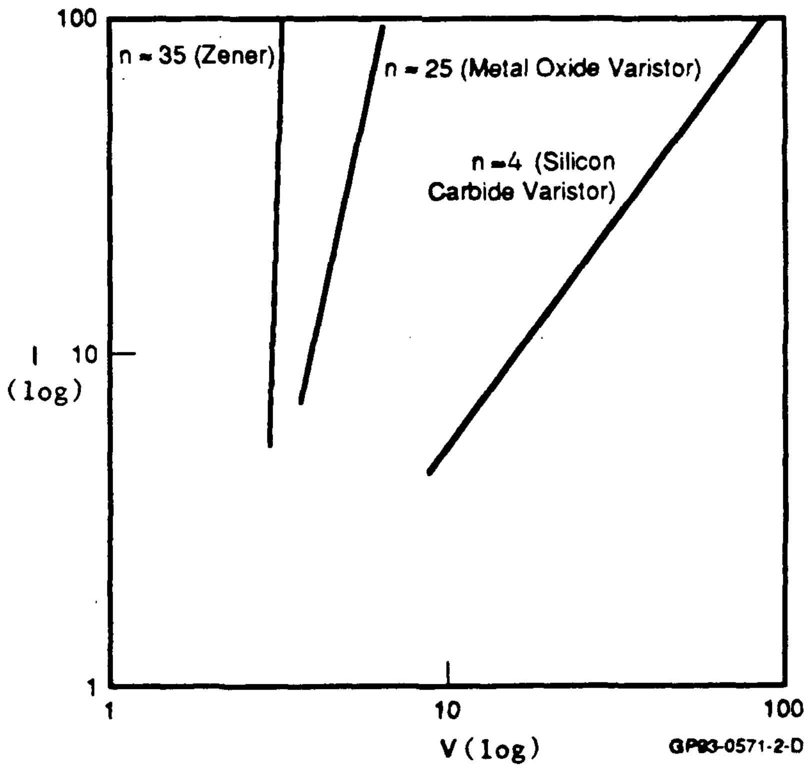

Figure 11. <u>V-I Characteristics for Various Values of n</u>

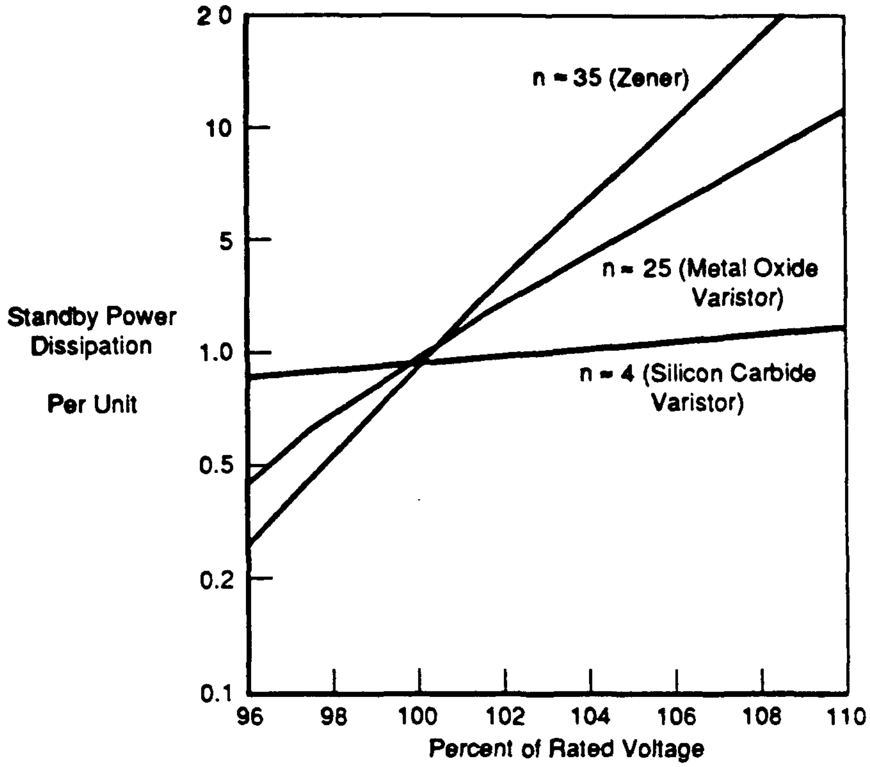

Figure 12. Standby Power Dissipation

The attributes listed above are available in varying degrees depending on the device in question. Table 1 summarizes the advantages and disadvantages of the various protection devices. The clamping ratio of a thermistor is not listed since they are not used to clamp voltages. The Surgector, while not a generic device, is included due to its simplicity and simple on or off operation. The SG1543 and SMARTPOWER were not included due to their relative complexity. Unfortunately, there is no single transient protection scheme or device which can provide protection against all possible transients. Devices all have their niche whether it be high power dissipation, quick reaction times, available voltage ratings, precise clamping voltages, cost, size, operating temperatures, capacitance, etc. The following paragraphs will highlight the pros, cons and application of the various devices which are used in transient protection schemes.

1.6.1 Transient Suppression Diodes

Transient suppression diodes (TSD) are two terminal semiconductors with very sharp reverse voltage breakdown characteristics at a specific voltage.

Under forward bias conditions, a TSD's V-I characteristic is identical to a normal diode (see Figure 13a). But, when subjected to reverse bias, the TSD will breakdown at a specific voltage and begin conducting in the avalanche mode. The circuit symbol for a TSD is shown in Figure 13b. As

Device	Clamping Ratio	Response Time	Leakage Current	Allowable Currents	Voltage Ranges	Size
Zener(TSD)	1-1.5	10^{-12} s	Medium	50A (1ms) 600A (200ns)	5-400V	Small
Thyristor(SCR)	~0	10^{-9}- 10^{-6} s	Low	2000A (1ms)	5-800V	Medium
Metal Oxide Varistor	1.25-2	10^{-9}- 10^{-6} s	Medium	6500A(1ms)	5-1200V	Medium
Spark Gap or Gas Tube	~0	10^{-6}- 10^{-5} s	Very Low	10000A (1ms)	90-20kV	Large
Surgector	~0	10^{-12}- 10^{-9} s	Low	200A (20μs)	30-270V	Medium
Thermistor	NA	10^{0} s	NA	–	–	Small
Fuse/Circuit Breaker	0	10^{-3}- 10^{0} s	NA	–	–	Medium
Ideal	1	10^{-12} s	Very Low	Very High	Low-High	Small

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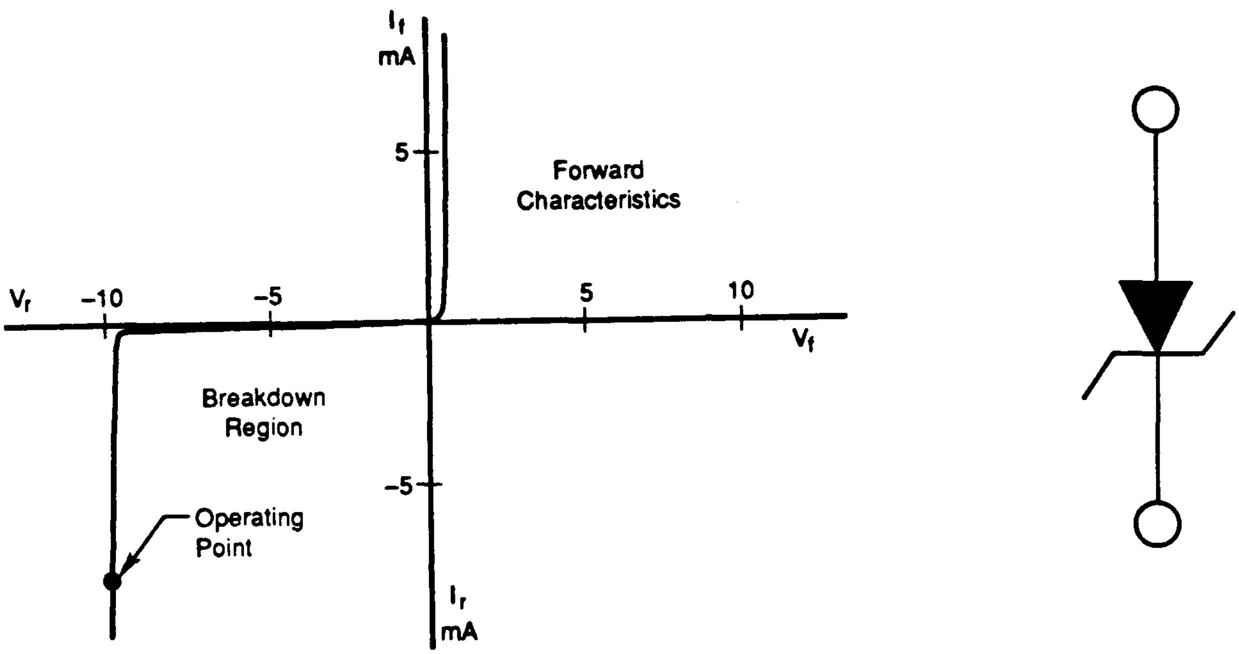
Table 1. Transient Protection Device Comparison

illustrated, the symbol and the V-I curve for a TSD is identical to a that of a Zener diode. TSDs differ from Zeners in that they have been designed to dissipate heat more efficiently and the surface geometry of the diode junction has been designed to eliminate localized high electric fields which allow reverse leakage current on the surface of normal Zener diodes. This ensures that bulk breakdown occurs at a specific reverse voltage.

TSDs are used to redirect transients away from the circuit that is being protected. As a transient suppressor, TSDs offer several major advantages over other devices. Response time to transients is measured in pico-seconds, several orders of magnitude better than other devices. TSDs are available for lower voltage applications, offer better clamping ratios and the capacitance of a TSD is minimal. The major disadvantage of a TSD is its limited power dissipation ability when compared to other devices. This is mainly due to the small junction area of the diode which results in high current densities and high junction temperatures. Additionally, the TSD maintains a working voltage across its terminals which causes a high power dissipation (power equals the product of voltage and current).



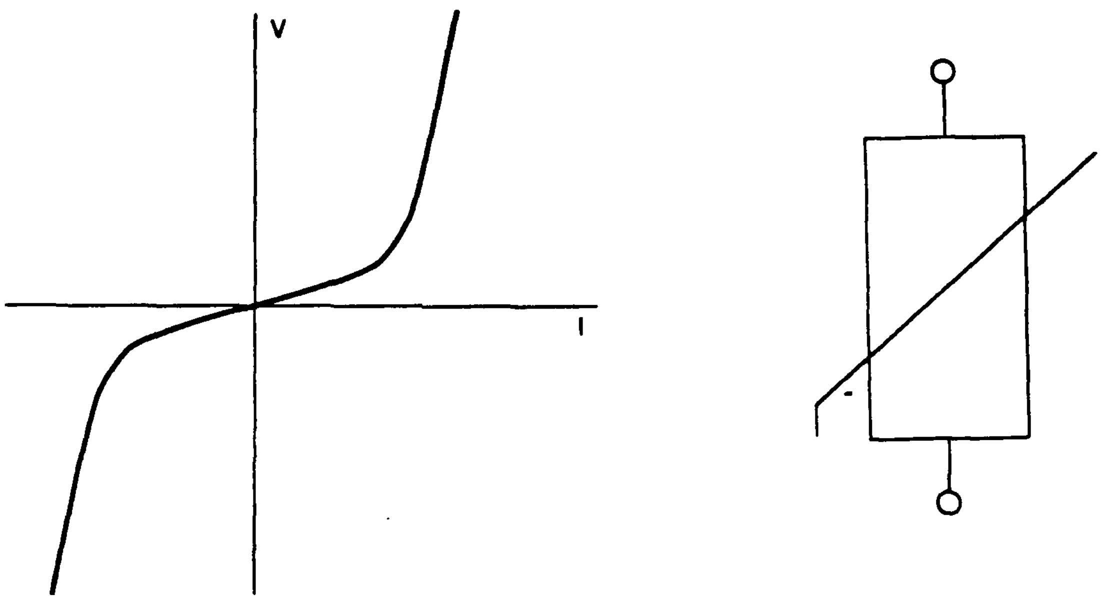
(a) (b)

Figure 13. Transient Suppression Diode Characteristics

When a TSD fails, it will generally fail short for long enough to allow a fuse or circuit breaker, somewhere in the power supply input, to open. Failing short is the result of current filamentation discussed in section 1.2. A TSD can fail open if current filamentation continues long enough to melt the silicon, but it will almost always occur after failing short allowing enough time for a fuse or circuit breaker to open. Failing short guarantees a zero voltage drop across the circuits to be protected. Devices that fail open expose the protected circuit to the full transient condition and will not be able to divert the overvoltage condition.

1.6.2 Varistors

Varistors are voltage dependent, nonlinear resistors where the current (I) varies as a power of the applied voltage (V), or $I = KV^n$ (where n is typically 2 to 4). As illustrated in Figure 14a, varistors possess symmetrical V-I characteristics similar to back-to-back Zener diodes. Their schematic representation is shown in Figure 14b. They are two terminal



(a) (b)

Figure 14. Varistor Characteristics

devices made of either silicon carbide or, more commonly, metal oxides. The metal oxide varistor (MOV) is composed primarily of zinc oxides with small additions of bismuth, cobalt, manganese and other metal oxides. The body of the varistor consists of a matrix of conductive zinc oxide grains separated by grain boundaries which act as PN junctions. These boundaries are responsible for blocking conduction at low voltages and nonlinear conduction at higher voltages. These numerous PN junctions distribute the current evenly throughout the device resulting in uniform heat distribution allowing the varistor to be used in high power situations.

When wired in parallel with the circuit to be protected, varistors do not affect normal circuit operation. When a transient voltage exists, the device begins to conduct when the turn-on voltage is reached. The voltage is then clamped while the current increases exponentially, just as in the TSD. However, the clamping ratio of a varistor is not as good as a TSD's. Therefore, under a given transient condition, the varistor will allow the voltage to rise to a higher clamping level than the TSD would. The response time of varistors is measured in nanoseconds and the capacitance of a varistor can become a factor in circuit performance given the right conditions. The major disadvantage of varistors, however, is their propensity to explode under energy conditions significantly in excess of rated values resulting in expulsion of hot material. Siemens, a MOV manufacturer, recommends physically shielding varistors to avoid damaging other components.

1.6.3 Thermistors

Thermistors are thermally sensitive resistors which can exhibit either positive or negative coefficients of resistance when their body temperature changes. Figure 15a illustrates this characteristic for both types of thermistors. Thermistors are made of manganese, nickel and cobalt oxides. These materials are mixed in suitable proportions and combined with binders before being pressed or extruded into the proper shape. The circuit symbol used for thermistors is shown in Figure 15b.

The positive and negative coefficient of resistance allows thermistors to be used in unique functions. For example, when circuits are initially energized, a large transient in-rush current can be induced as the circuit charges a capacitor or by the low resistance of a cold filament. To limit in-rush current at turn-on, a thermistor with a negative coefficient of resistance can be placed in series with the primary supply. When the supply is energized, the cold thermistor limits the current flow due to its high resistance. Once current begins to flow, the device heats up and the resistance begins to drop allowing more current to flow. Ultimately, the thermistor reaches a resistance at which it dissipates negligible amounts of energy and allows the circuit to function normally. Positive

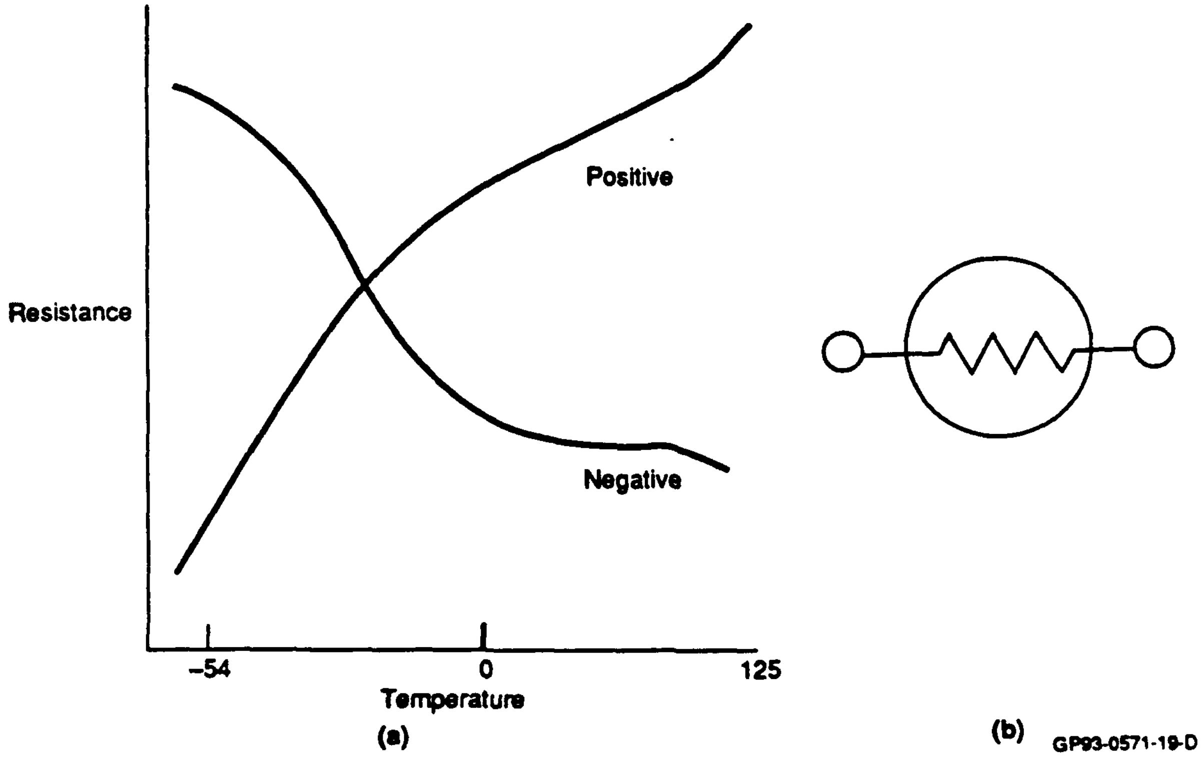


Figure 15. Thermistor Characteristics

coefficient thermistors can be used to limit current during transient conditions by placing the device in series with the load. Under normal circuit conditions, the device presents a negligible resistance. If an overcurrent condition exists, the device begins to heat up raising the resistance until the current is controlled.

The major drawback of thermistors is the heating and cooling hysteresis (or time constant) they exhibit. For example, under normal operating conditions, a thermistor used as an in-rush current limiter will be heated to its operational temperature, thus exhibiting negligible resistance. If a transient condition suddenly removes power from the circuit, the power supply will shut down. When the transient condition ends, the power supply will turn back on. However, since the thermistor can not cool down instantly, it is still at its operational temperature and, therefore, is incapable of limiting the in-rush current. Alternatively, a positive coefficient thermistor which has limited an overcurrent situation will continue to inhibit normal circuit operation until enough time has elapsed for it to cool after the transient is removed.

1.6.4 Silicon Controlled Rectifier (SCR)

The SCR, also known as a thyristor, is a four layer PNPN device with three terminals (see Figure 16). Basically, it is a diode with a control gate. The device will not conduct (other than a small leakage current)

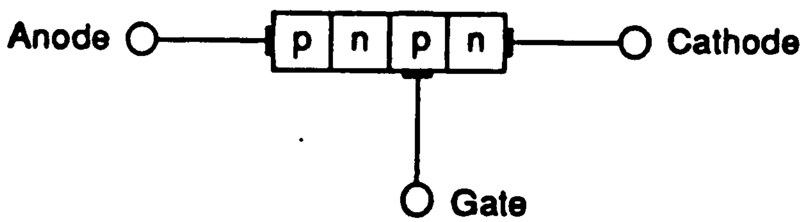


Figure 16. SCR Construction

when forward biased until a voltage, referred to as the breakover voltage, is reached. At this point, the current increases rapidly and the voltage drop decreases drastically allowing the SCR to divert large amounts of current without dissipating much power. The voltage applied to the gate serves to decrease the breakover voltage point. Once the breakover voltage has been exceeded, the SCR will conduct current as long as a forward bias is maintained, regardless of the gate voltage or the voltage across the other two terminals. The gate can not be used to shut down the SCR. To stop current flow through the SCR, a reverse bias must be established. SCRs have specified turn on times in the nano- to micro-second range and require 10-100 microseconds of reverse bias to reestablish forward blocking. The circuit symbol and the V-I characteristic for an SCR are shown in Figures 17a and b.

1.6.5 Gate Turn Off or Gate Controlled Switch (GTO or GCS)

The GTO/GCS device is an SCR which can be turned off by applying a negative signal to the gate and is sometimes referred to as a turn-off thyristor. This is different from an SCR in that the voltage across the SCR's anode and cathode must be reversed or eliminated to turn it off. This would be useful in a circuit where it is not desirable to totally eliminate the applied voltage to the circuits in order that they may be reset. The circuit symbol for one of these devices is shown in Figure 18. V-I characteristics are identical to Figure 17a.

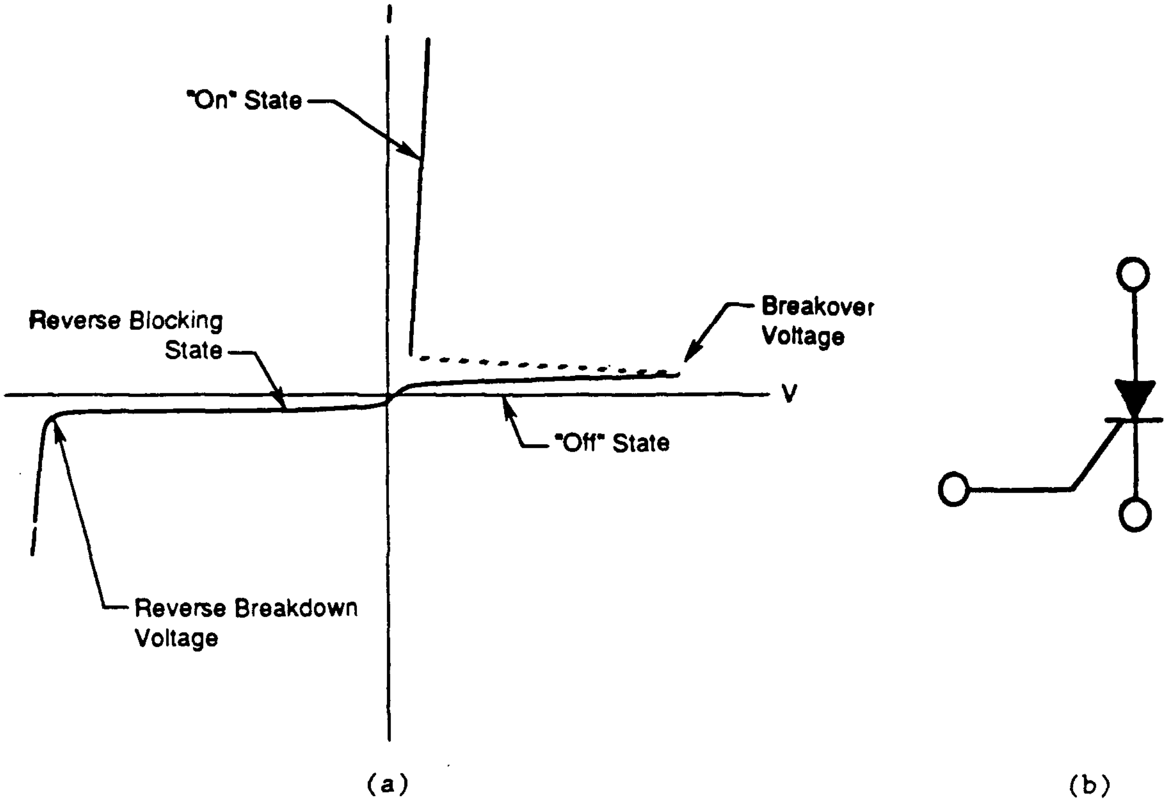


Figure 17. SCR Characteristics

1.6.6 Gas Discharge Tubes (GDT)

GDTs operate by switching from a very high impedance to a very low impedance in the presence of a high voltage potential (breakdown voltage). This switching action occurs when the inert gas in the tube ionizes and begins to support conduction in the glow region. Increasing current causes the device to conduct with an arc, maintaining a constant voltage (typically 15 volts) regardless of the current flow. The GDT will stop conducting when the voltage is dropped below the arc voltage. Since the voltage necessary to maintain an arc is much less than the voltage necessary to initiate an arc and may be less than typical operating voltages, the arc will be maintained after the circuit voltage returns to normal. Therefore, a method is needed to extinguish the arc. The major drawback to

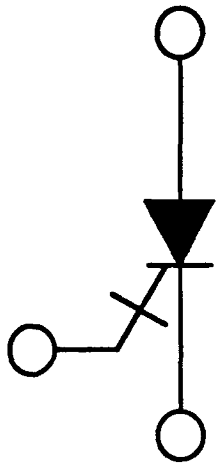


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Figure 18.

GTO/GCS Schematic Symbol

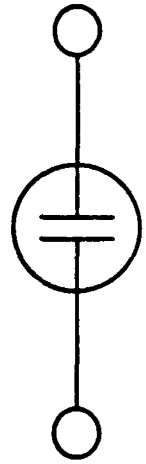

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Figure 19.

Gas Discharge Tube Schematic Symbol

these devices is the time it takes for the transient to ionize the gas and the subsequent transition time to arc (typically microseconds). The circuit symbol for a GDT is shown in Figure 19. The V-I characteristic of a GDT is similar t t.at of Figure 17a.

1.6.7 Transient Monitors/Controllers

There are many integrated chip suppliers who manufacture monolithic power supply monitoring devices. These devices can sense overvoltage, over-current, undervoltage and overtemperature conditions. Once sensed, the devices respond by triggering crowbars or sending shutdown commands to the regulator. Several examples have been included here to highlight the capabilities of these chips.

The Silicon General SG1543 is a monolithic integrated output supervisory circuit which provides overvoltage and undervoltage sensing, current sensing and an SCR crowbar trigger driver in a standard 16 pin DIP. The voltage monitors can respond to transients within 400 nanoseconds, but longer delays can be selected via appropriate choices of external capacitors. The current sensor can respond within 200 nanoseconds. The output response can be configured for fault indication, voltage limiting, power supply shutdown or any combination of the three. The overvoltage output is directly connected to the onboard SCR driver. A remote activate pin for the SCR driver can be connected to the current sensor output or some other source for additional capabilities.

The RCA Surgector is a transient suppressor which consists of a thyristor with a Zener diode diffused across the gate region. This is accomplished on a monolithic substrate. The Surgector combines the quick response of a Zener and the large current capacity of an SCR. When the Zener begins conducting, the gate of the SCR is energized turning the SCR on. The Surgector turns off when the current drops below the holding current. The Surgector is capable of handling up to 10kV/uS dv/dt and is capable of turning on in nanoseconds. The schematic representation and the circuit symbol are shown in Figure 20. The V-I characteristic is similar to that of Figure 17a.

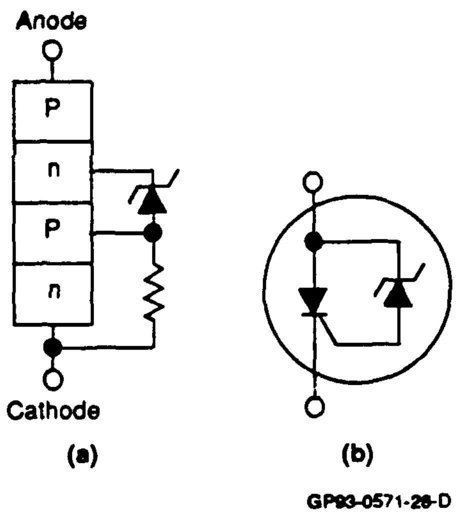

Figure 20. RCA Surgector

SMARTPOWER is a monolithic integrated chip manufactured by Motorola. The device monitors for over voltage and over temperature conditions. When these conditions exist, an onboard SCR is fired to redirect the transient condition. The device can switch on within 5 microseconds and shunt up to 35A of continuous current. An external line control is available to switch the SCR on if desired.

1.7 Applications of Transient Protection Devices

The following paragraphs will illustrate various ways of using transient protection devices as a means to clamp voltages, divert currents or attenuate transients. These designs will protect the power supply and the load from internally and externally generated transients.

1.7.1 Voltage Clamp

To protect a power supply from voltage spikes generated on the main power bus or from spikes generated at the load, TSDs should be placed in parallel with the transient source and/or in parallel with the device to be protected. The output TSD will also protect the load from overvoltages generated by the supply. Figure 21 illustrates the use of a TSD at the input to a power supply and at the load. In these installations, the voltage at the input or output will be clamped at the rated value of the TSD. Varistors can be used to clamp the input or output of a power supply in the same manner as a TSD. For circuits subject to very high voltage

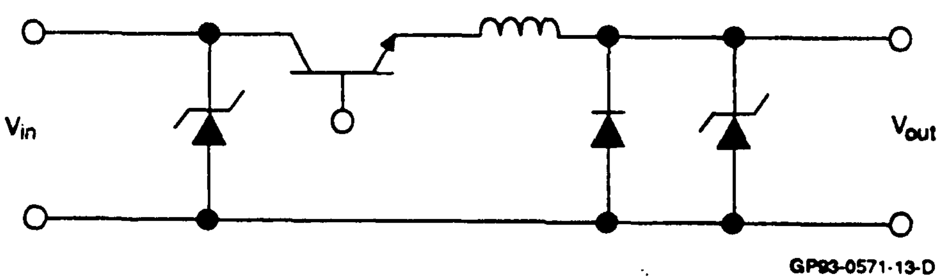

Figure 21. Voltage Clamp using TSDs

transients and subsequent high current transients, a gas discharge tube can be used to replace the TSD.

If it is essential that voltages be maintained under some specified value due to the cost of the equipment or if it is acceptable to lose functionality during transients, a crowbar can be used to clamp over voltages. Figure 22 illustrates a crowbar device consisting of a resistor, a varistor (or TSD) and an SCR. When the voltage rises to the point where the the TSD begins to conduct (or breakover), a voltage will be induced across the resistor and will turn on the SCR. When the SCR turns on, the voltage across the output will drop to approximately one volt. This technique has the advantage of a TSD's quick response and the SCR's high current capabilities. While this is a very simple and inexpensive design, it suffers from two disadvantages - 1) When the SCR begins to turn on, the voltage and current across the TSD begins to fall, thus robbing the

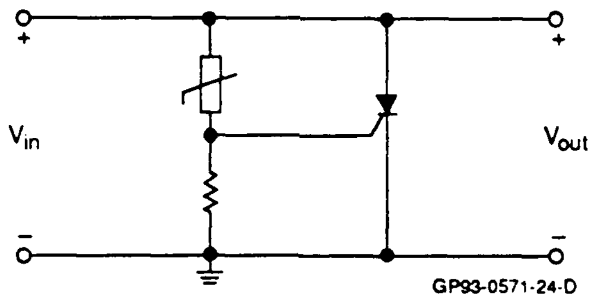

Figure 22. Crowbar Implementation

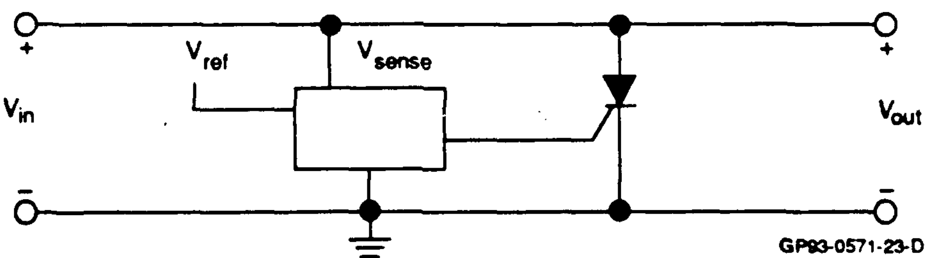

Figure 23. Latched Crowbar Implementation

gate drive for the SCR resulting in a "slow" gate turn on. A method of latching the gate drive on may be desirable if space permits. This method is illustrated in Figure 23 where a voltage monitor has been used to supply the necessary gate drive to fire the SCR. 2) The power must be totally removed, to reset the SCR, before operation can resume. A GCS or GTO, which can be used in identical applications as SCRs, could be used to avoid this problem.

When SCRs, GCSs or GTOs are used to suppress voltage transients, some form of current limiting is necessary to avoid damage. Recall that an SCR presents a very low impedance path and will therefore allow large amounts of current to flow. In order that the power supply remains protected at times of sustained high currents, some type of fusing device should be used on the input supply. It should be selected so it will not open unless the internal current limiting features (discussed in the next paragraph) fail.

1.7.2 Current Limiting

Current limiting encompasses several different techniques which are designed to limit current under differing conditions. Overcurrent conditions can be caused by several factors including shorted outputs, shorted transient protection devices, start-up transients (discussed in the next paragraph) and undervoltage input conditions.

There are two commonly used methods to implement short circuit protection other than using a control circuit to shut down the supply - the constant current protection and the current foldback protection. Constant current protection puts an upper limit on the current that can flow through the load. Once the current reaches this limit at some load impedance, the current becomes constant no matter what the impedance drops to, as illustrated in Figure 24. In a linear power supply, this situation produces an upper limit on power dissipation in the power transistor since the collector to emitter voltage is at a maximum when the load voltage is at a minimum (short circuit). Foldback circuit protection will begin to limit the current at the same load impedance as the constant current method, but as the impedance continues to drop, the current begins to decrease, or foldback, as shown in Figure 24. Foldback current protection greatly reduces the power dissipation under shorted conditions since the current (short circuit) is at a much lower level than normal operating currents. The following is an explanation of how these techniques work.

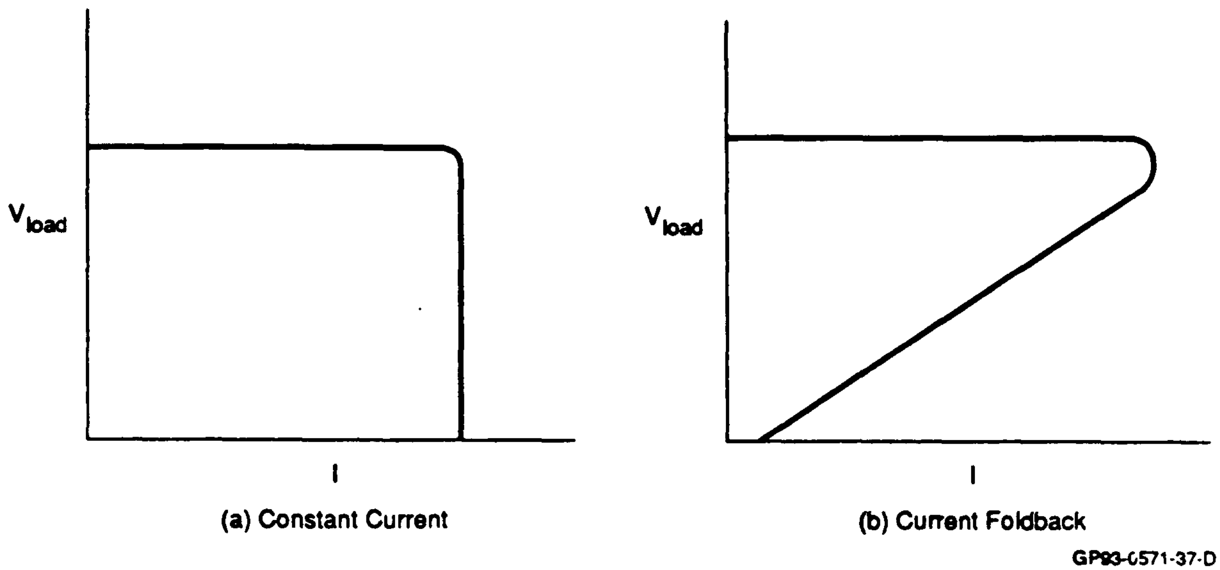

Figure 24. Current Limiting V-I Characteristics

A simple constant current circuit for a linear power supply is shown in Figure 25. As the current increased through R1, the base to emitter voltage of Q2 will reach a point where Q2 starts to conduct. Base current for Q1 is diverted through Q2 to the load. As the load impedance decreases, Q2 will allow only enough base current in Q1 to maintain the original current level in R1 which initially caused Q2 to start conducting.

Adding R3 and R4 to the constant current circuit creates a simple current foldback circuit as shown in Figure 26. To reach the trip point where the current begins to foldback, the voltage across R1 minus the voltage across

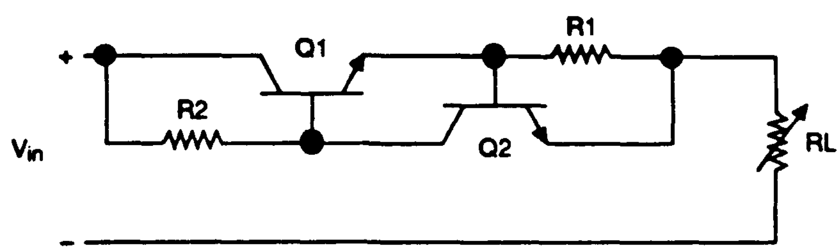

Figure 25. Constant Current Implementation

R3 must equal the voltage needed for Q2 to conduct. At this point, Q2 begins to reduce the base drive for Q1 and Q1 begins to reduce the voltage across the load and the R3/R4 divider. As the load impedance decreases the voltage across R3, less voltage is required across R1 to keep Q2 turned on. Thus, the current required to hold the circuit in current limit is continually reduced as the load impedance is reduced.

Figure 27 illustrates the use of a thermistor as an overcurrent limiter. A positive coefficient of resistance should be used in this application.

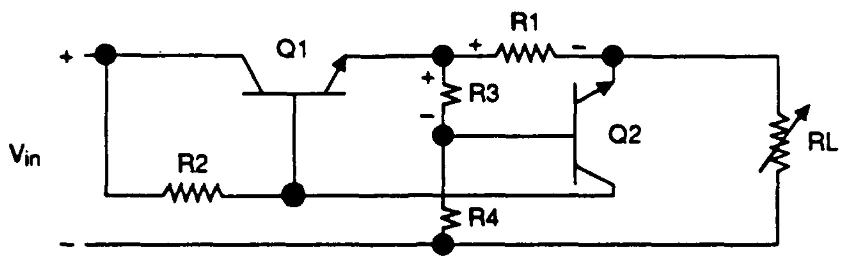

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Figure 26. Current Foldback Implementation

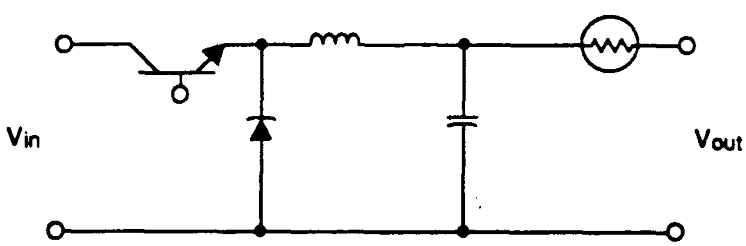

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Figure 27. Thermistor Current Limiting

1.7.3 Start-up Transient Suppression

To prevent high current from damaging power supplies during power up, two methods are commonly used. They are:

1) The first method uses some form of current limiting circuit in the input side of the power supply. This can take the form of a resistor or thermistor with a negative coefficient of resistance in series with the supply line as illustrated in Figure 28. Unfortunately, this method will increase steady state power dissipation unless the limiter is switched out of the circuit after steady state conditions are achieved. Switching can be accomplished with relays, transistors or SCRs. Thermistors do not significantly increase steady state power consumption, but they have a large thermal time constant which does not allow them to quickly respond to changing conditions on the power line. For example, if the power supply is at steady state conditions and the power is removed and immediately reapplied, the thermistor will not cool sufficiently during the off time to provide current limiting resistance when the power is reapplied.

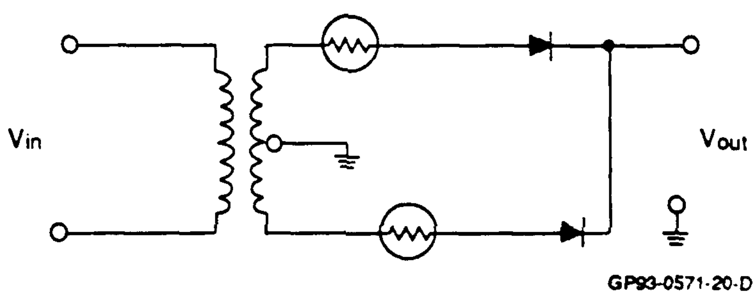


Figure 28. Thermistor In-rush Current Limiter

2) The second method limits the on-time of the pass transistor by controlling the reference voltage (which the output voltage is compared to for regulation), thus allowing the output voltage to come up more slowly.

The overshoot voltage caused by start up transients will be controlled by the two methods listed above. An alternate means to ensure low overshoot is to dissipate the energy released by the inductor in a snubber circuit. Snubbing circuits are described in the next paragraph.

1.7.4 Transistor/Inductor Snubbing

Transients produced by switching voltages and currents with a transistor can be suppressed with snubber circuits. These circuits can reduce the peak voltage and currents which cause ringing that exceeds component electrical ratings and they can reduce the heat dissipated in switching transistors. Much of the peak power dissipated in the switching components can be shifted to the snubbing circuits without increasing the overall power dissipation of the circuit since the power will be dropped over the transistor if not over the snubber. Implementation of these snubbing circuits will decrease the possibility of thermal degradation of the transistor, and therefore, enhance the reliability.

Prior to a transistor being turned on, the collector to emitter voltage is at its highest state and the collector current is at its lowest state. Ideally, as the transistor turns on, the current would be delayed until the voltage has dropped to its minimum on value thus minimizing the power dissipated by the transistor, resulting in minimum junction temperatures and highest reliability. Unfortunately, the current rapidly begins to flow while the voltage begins to drop more slowly. In many applications, the stray wiring inductance helps to limit the current rate of rise; however, if it does not, the transistor temperature can rise above optimum levels. This higher temperature leads to higher collector to emitter voltages and degraded turn-off transition times which will lead to even higher temperatures, a form of thermal runaway called switching thermal runaway (STR). STR may or may not reach equilibrium prior to device failure. The turn-on snubber shown in Figure 29a will provide the delay in collector current rise necessary to avoid STR. The inductor supplies the necessary delay while the diode-resistor (Figure 29b) provides a dissipative path for the inductive voltage spike generated by the inductor when the transistor turns-off.

When a transistor is turned off, the voltage across the collector-emitter begins to rise before the current declines. As a result, the power dissipated in the transistor is very high since large values of current and voltage are present simultaneously. The turn-off snubber of Figure 30a will prevent this by delaying the collector to emitter voltage rise until the current has time to decay. Without this type of protection, the STR phenomenon may occur. Additionally, the turn-off snubber will perform as a current sink for the transistor, redirecting the collector current. The turn-off snubber can be modified as shown in Figure 30b and c. However, this modification will only help dissipate the inductive voltage spike, it will not delay the collector to emitter voltage rise.

The voltage spike generated by an inductor when the current is being shut down can be controlled by placing a snubber across the inductor as shown in Figure 29b,c and d. A diode and resistor (29b) combination placed in parallel with the inductor such that the diode is forward biased when the output voltage exceeds the input voltage by the voltage drop of the diode.

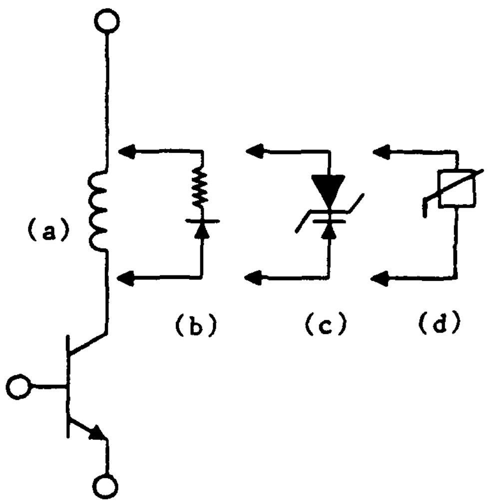


Figure 29. Turn-on Snubber

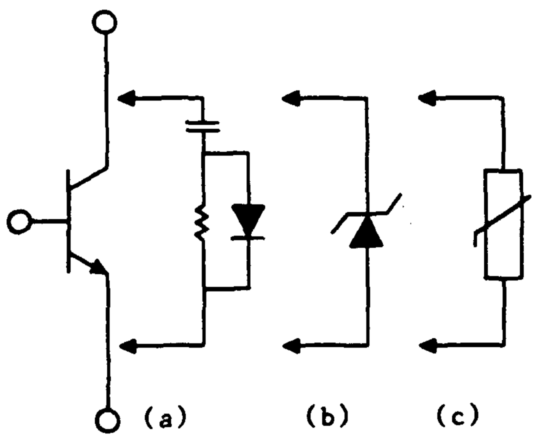


Figure 30. Turn-off Snubber

The Zener - diode (29c) combination will control the voltage spike only if the spike exceeds the threshold of the Zener. A varistor (29d) could be used instead of the diode/resistor combination, but control of the overshoot would not be as good.

Chapter 2

Power Supply Design Guidelines

2.0 Introduction

Task 2 of the statement of work required the development of power supply design guidelines which, if followed, would enhance the reliability of the power supply by decreasing its susceptibility to transients. These guidelines have been sorted into several groups depending on their nature. Each guideline presented is supplemented with the rationale for the guideline. Additionally, the source of the guideline is included if it was from only one or two sources. If the guideline was found in multiple sources, the sources were not included.

2.1 Top Ten Design Guidelines

1. Procurement specifications often do not clearly specify the type or amount of transient protection necessary to ensure high reliability in power supplies. This obviously leaves loopholes that allow the vendors to take shortcuts in the design to reduce the development and production costs. Good design practice must consider the transient conditions throughout the entire power supply including input power line voltage spikes, input current surges, transient voltage and current waveforms created during the switching transitions of the power transistors, current limiting outputs, output overvoltage protection, and the radio frequency (RF) power generated by leakage inductance and stray capacitance in the switching circuits. As a minimum, the designer must identify the transients (voltage and current) which the circuit is expected to see (common and transverse mode) at the input, specify the source impedance of the input, specify the type of protection required and identify the type of load for which the power supply will be providing power.

2. Protection from in-rush current during power up must be provided. This will protect the load and output filters from overshoot voltages and the input rectifiers and the pass transistor from the in-rush current. Methods include using control circuitry to limit pass transistor on-time during power up and current limiting resistors installed in the input lines. If efficiency is a concern, a design which switches the limiting resistor out after operating voltages have been reached should be considered. Examples of "switches" include thermistors, relays and SCRs. A small capacitor on the voltage reference input to the regulator will limit the on-time of the transistor during power up. See Chapter 1 for more details. STARTUP TRANSIENTS IN SWITCHING REGULATORS (Ref. 28), SWITCHING AND LINEAR POWER SUPPLY DESIGN (Ref. 25)

3. Transformers must be selected so they will not saturate when exposed to normal balanced circuit drive voltages. If a balanced drive can not be achieved through proper design, compensation techniques must be incorporated to achieve a balanced volt-second product. A volt-second product is defined as the area enclosed by the voltage waveform when plotted with time as the abscissa and voltage as the ordinate. A balanced volt-second product is obtained when the area of the positive volt-second product is equal to the area of the negative volt-second product. MCDONNELL DOUGLAS ELECTRONICS SYSTEMS COMPANY

4. Minimize the number of combined mechanical and electrical attachment points used. Mechanical attachments which become loose cause intermittent open circuits to appear. If they are required, use locking nuts, thread locks (Loctite TM*) and torque the nuts down. Avoid using materials with widely varying thermal coefficients of expansion in the attachments, otherwise they will work loose over time.

5. When selecting transformers or inductors for a design, choose designs and manufacturing techniques which have been field proven. The design of the winding to lead interface is very critical and will readily fail if proper considerations for strain relief are not provided.

* Loctite TM is a registered trademark of Loctite Corporation

6. Use flex wiring (equivelant to flexible printed circuit boards - not to be confused with ribbon cable) wherever practical in wire routing throughout the power supply. The physical relationship of wires in a bundle varies from unit to unit which causes noise levels and transient propagation to vary from one unit to the next. With flex wiring, the spacing is uniform and will help keep transients and noise at a consistent and predictable level. Once these values are predictable, the circuit can be designed to accommodate them, enhancing reliability and performance. MCDONNELL DOUGLAS ELECTRONICS SYSTEMS COMPANY

7. Qualification and reliability development test requirements should be expanded to include subjecting power supplies to specified transient conditions and verifying satisfactory performance. MCDONNELL AIRCRAFT COMPANY

8. Field effect transistors (FET) are recommended for most switching power supply applications. Their positive temperature coefficient makes them easier to operate in parallel and tends to offset.the transformer core saturation problem. If a FET in parallel begins to conduct more current than the other one, it will heat up inducing a higher resistance which begins to limit the current. With respect to the core saturation problem, as the current spike passes through the transistor, it will heat up and increase in impedance. Once the impedance increases, the voltage dropped across the transistor will increase thus altering the volt-second product of the transformer in a manner which will tend to bring it back towards balance. Additionally, FETs can be operated at higher frequency and the drive circuit is easier to design than for equivalent bipolar transistors. MCDONNELL DOUGLAS ELECTRONICS SYSTEMS COMPANY

9. Base circuitry should be designed to drive the transistor into saturation very fast and then decay to a value which will barely keep the transistor in saturation. This will minimize the power dissipated during switching and will prepare the transistor for a quick turn off by minimizing the charge stored in the base. A base drive which has been designed to reverse bias the base to emitter during turn off will be much more effective in achieving a quick turn off since the reverse bias will remove the charge stored in the base.

10. Require stability, stress and worst case analysis on power supplies. The stress analysis should be supported with measured data from breadboard or engineering models since the current and voltage wave forms induced during switching action are difficult to calculate accurately. MCDONNELL DOUGLAS ELECTRONICS SYSTEMS COMPANY

2.2 Procurement Specification Language Guidelines

1. Procurement specifications often do not clearly specify the type or amount of transient protection necessary to ensure high reliability in power supplies. This obviously leaves loopholes that allow the vendors to take shortcuts in the design to reduce the development and production costs. Good design practice must consider the transient conditions throughout the entire power supply including input power line voltage spikes, input current surges, transient voltage and current waveforms created during the switching transitions of the power transistors, current limiting outputs, output overvoltage protection, and the radio frequency (RF) power generated by leakage inductance and stray capacitance in the switching circuits. As a minimum, the designer must identify the transients (voltage and current) which the circuit is expected to see (common and transverse mode) at the input, specify the source impedance of the input, specify the type of protection required and identify the type of load for which the power supply will be providing power. The transient waveforms in terms of peak voltages, peak currents, rise times and durations must be specified.

2. The type of protection required should be based on trade-off studies considering the cost of the unit, the added cost of protection circuitry, the potential operational environment, the cost to repair the item, the cost to spare extra power supplies, the impact of a failure on the system/subsystem, etc. This will allow the design to reflect the minimum life cycle cost.

3. Specify the minimum hold-up time (the time a power supply must continue to provide an output after the input power has been removed) necessary for the design. NAVMAT 4855-1 (Ref. 43)

4. Avoid using fuses or circuit breakers internal to the power supply. NAVMAT 4855-1 (Ref. 43)

2.3 General Transient Protection Guidelines

1. Place the protection device between all potential sources of transients and the device to be protected. It is best to place the device as close to the circuitry to be protected as possible to avoid transients induced by parasitic impedances of the transmission lines. An additional device could be placed close to the transient source.

2. In a current diverter, the transient current is divided between the diverter and the load at a ratio determined by the impedance of each. To help ensure that the impedance of the diverter is much less than the load impedance, an impedance should be placed in series with the load. An inductor selected to offer negligible impedance at the operating frequency (to minimize operating power consumption) and a high impedance at the transient frequency should be used.

3. When using a voltage clamp across a load, the clamp regulates the voltage in a voltage divider network with the transient source. If the source has a very low impedance, the clamp will not be effective. Therefore, an impedance should be placed in series with the load and clamp if the source impedance is undefined.

4. When using a crowbar device to protect against overvoltage, the crowbar should be selected so that it will not fail before the power transistor burns open if the transistor is failed short. If the crowbar device fails first, the overvoltage condition will be restored and the load will be unprotected. Fuses can be installed in the primary to protect against this possibility. The crowbar will provide quick protection while the fuse will provide "permanent" protection.

5. Protection from in-rush current during power up must be provided. This will protect the load and output filters from overshoot voltages and the input rectifiers and the pass transistor from the in-rush current. Methods

include using control circuitry to limit pass transistor on-time during power up and current limiting resistors installed in the input lines. If efficiency is a concern, a design which switches the limiting resistor out after operating voltages have been reached should be considered. Examples of "switches" include thermistors, relays and SCRs. A small capacitor on the voltage reference input to the regulator will limit the on-time of the transistor during power up. See Chapter 1 for more details. STARTUP TRANSIENTS IN SWITCHING REGULATORS (Ref. 28), SWITCHING AND LINEAR POWER SUPPLY DESIGN (Ref. 25)

6. Sequence the turn-off/turn-on logic in an orderly and controllable manner to prevent voltage overshoot. NAVMAT 4855-1 (Ref. 43)

2.4 General Power Supply Guidelines

1. Use flex print wiring (equivelant to a flexible printed circuit board not to be confused with ribbon cable) wherever practical in wire routing throughout the power supply. The physical relationship of wires in a bundle varies from unit to unit which causes noise levels and transient propagation to vary from one unit to the next. With flex print wiring, the spacing is uniform and will help keep transients and noise at a consistent and predictable level. Once these values are predictable, the circuit can be designed to accommodate them, enhancing reliability and performance. MCDONNELL DOUGLAS ELECTRONICS SYSTEMS COMPANY

2. Use printed circuit boards (PCB) instead of point to point wiring. NAVMAT 4855-1 (Ref. 43)

3. When point to point wiring must be used, use stranded wire only.

4. Derate voltage/current/power/frequency/thermal ratings of components to applicable program levels.

5. Multiplier stacks used for high voltage applications (10-20kV) should be designed such that the diodes and capacitors are not subjected to more

than one half their manufacturer's rated specifications to avoid potential arcing problems. SWITCHING AND LINEAR POWER SUPPLY DESIGN (Ref. 25)

6. Transformers must be selected so they will not saturate when exposed to normal balanced circuit drive voltages. If a balanced drive can not be achieved through proper design, compensation techniques must be incorporated to achieve a balanced volt-second product. A volt-second product is defined as the area enclosed by the voltage waveform when plotted with time as the abscissa and voltage as the ordinate. A balanced volt-second product is obtained when the area of the positive volt-second product is equal to the area of the negative volt-second product. MCDONNELL DOUGLAS ELECTRONICS SYSTEMS COMPANY

7. Minimize the number of combined mechanical and electrical attachment points used. Mechanical attachments which become loose cause intermittent open circuits to appear. If they are required, use locking nuts, thread locking compounds (such as Loctite TM) and torque the nuts down. Avoid using materials with widely varying thermal coefficients of expansion in the attachments, otherwise they will work loose over time.

8. When selecting transformers or inductors for a design, choose designs and manufacturing techniques which have been field proven. The design of the winding to lead interface is very critical and will readily fail if proper considerations for strain relief are not provided.

2.5 Silicon Controlled Rectifier Guidelines

1. The di/dt rating of an SCR should be matched to the expected transient. A transient di/dt which is too high will cause localized junction destruction due to overheating while waiting for the conduction region to expand beyond the original turn on point. Over driving the gate on an SCR will increase the di/dt capability of the device. An inductor placed in series with the SCR will limit the di/dt, but will also slow down the voltage reduction on the power bus. A resistor placed in series with the SCR can help dissipate surge current, but it will also lengthen the time to drop the voltage on the bus.

2. Motorola does not recommend using a Zener sensing circuit to fire an SCR (a Zener in series with a resistor where the voltage between the two is used to fire the SCR gate). The setup provides slow gate drive and when the gate begins to turn on the SCR, the gate drive is depleted minimizing the portion of the junction which is conducting. Additionally, the turn on voltage can only be adjusted by changing component values. Variations in the Zener's breakdown voltage and in the firing voltage/current of the SCR can produce large variations of crowbar voltages. MOTOROLA LINEAR/ SWITCHMODE VOLTAGE REGULATOR HANDBOOK (Ref. 6); SWITCHING AND LINEAR POWER SUPPLY DESIGN (Ref. 25)

3. Monitoring circuits provide advantages when using SCRs. Chips provide trip voltage adjustments, large gate drive, adjustable low temperature coefficient trip point, adjustable overvoltage duration before firing gate (to minimize noise induced tripping), status output and remote activation. The status can be used to shut down the power supply to avoid power dissipation in the SCR. The remote activation can be used to shut down the power supply whether a fault exists or not. MOTOROLA LINEAR/SWITCHMODE VOLTAGE REGULATOR HANDBOOK (Ref. 6)

4. When using a SCR as a crowbar providing overvoltage protection, a low impedance resistor-capacitor (RC) network should be placed in parallel with the gate-cathode leads. This will integrate narrow noise spikes which might otherwise turn on the SCR. Additionally, the gate-cathode resistor will ensure leakage current from the SCR drive will not fire the SCR and will reduce low frequency noise pick up that the capacitor may not filter out. SWITCHING AND LINEAR POWER SUPPLY DESIGN (Ref. 25)

5. When firing an SCR, ensure that the initial gate drive is a pulse approximately five times the normal continuous gate drive. This pulse should have a rise time of one microsecond or less and have a duration of at least ten microseconds before allowing the gate drive to return to normal levels. This practice will ensure a quick SCR turn-on which will maximize the conduction area at the junction. This in turn maximizes the life of the SCR. CHARACTERIZING THE SCR FOR CROWBAR APPLICATIONS (Ref. 36)

2.6 Switching Transistor Guidelines

1. To minimize switching losses when turning a transistor off, Unitrode advises using the minimum base drive which will drive the transistor into saturation. Higher base drive will increase switching losses without appreciable improvement of on state power dissipation. The low base drive minimizes the stored charge in the base region, which minimizes the fall time of the collector current when the transistor is turned off, which minimizes the power dissipated during switching (remember that the collector to emitter voltage (Vce) is the highest when the transistor is off, so you want low collector current (Ic). Secondly, a reverse biased base-emitter junction will help drive the stored charge out and will decrease the fall time. Finally, a snubber circuit should be used across the transistor to dissipate the inductive energy normally dissipated across the junction. UNITRODE POWER SUPPLY DESIGN SEMINAR HANDBOOK (Ref. 15)

2. To minimize the switching losses when turning a transistor on, the ideal situation is to delay the Ic until the Vce has dropped low. This can be accomplished by putting a small inductor in series with the Ic. The parasitic wire inductance and leakage inductance in transformers will sometimes be sufficient to delay Ic. A thorough analysis of the timing and waveforms present in a switching transistor should be conducted. The object is to switch the transistor on and off in a manner which minimizes dissipated power. UNITRODE POWER SUPPLY DESIGN SEMINAR HANDBOOK (Ref. 15)

3. The peak collector current should never exceed continuous current rating of a switching transistor. POWER SYSTEMS, INC. (Ref. 30)

4. Do not operate a power transistor in an unclamped inductive circuit. Avoids over stressing the transistor when the energy in the inductor is released after the current is interrupted. THE INTERPRETATION OF EOS DAMAGE IN POWER TRANSISTORS (Ref. 35)

5. The derated voltage specification for switch transistors in a push-pull converter must be selected to withstand voltage levels four times greater than the line voltage. The voltage is doubled since the push-pull arrangement uses a center tapped primary. The voltage can easily be

doubled again (or more) by the leakage inductance of the transformer. MCDONNELL DOUGLAS ELECTRONICS SYSTEMS COMPANY

6. Use isolated cases for switching power transistors, TO-3 type transistors which have chips mounted directly to the case must have an insulator between the case and chassis. If the insulator is one mil of Kapton, the capacitance from the TO-3 case to the chassis is approximately 220 pico-farads. High transient currents are injected into the chassis by these capacitors and must be returned to the source through the lowest impedance path available. MCDONNELL DOUGLAS ELECTRONICS SYSTEMS COMPANY

7. Field effect transistors (FET) are recommended for most switching power supply applications. Their positive temperature coefficient makes them easier to operate in parallel and tends to offset the transformer core saturation problem. If a FET in parallel begins to conduct more current than the other one, it will heat up inducing a higher resistance which begins to limit the current. With respect to the core saturation problem, as the current spike passes through the transistor, it will heat up and increase in impedance. Once the impedance increases, the voltage dropped across the transistor will increase thus altering the volt-second product of the transformer in a manner which will tend to bring it back towards balance. Additionally, FETs can be operated at higher frequency and the drive circuit is easier to design than for equivalent bipolar transistors. MCDONNELL DOUGLAS ELECTRONICS SYSTEMS COMPANY

8. Base circuitry should be designed to drive the transistor into saturation very fast and then decay to a value which will barely keep the transistor in saturation. This will minimize the power dissipated during switching and will prepare the transistor for a quick turn off by minimizing the charge stored in the base. A base drive which has been designed to reverse bias the base to emitter during turn off will be much more effective in achieving a quick turn off since the reverse bias will remove the charge stored in the base.

9. In applications where transistors must be mounted in parallel to carry the necessary current, matched transistors should be used. Alternatively, some technique to balance the current between the two transistors is

necessary. Balancing the current will ensure the transistors are both operated at the minimum power and thermal levels possible.

2.7 Analysis & Testing Guidelines

1. Ensure that the clamping voltage (at a specified peak pulse current and current rise time) is below the failure threshold of the equipment to be protected.

2. Ensure that measured peak voltages, peak power and peak currents do not exceed the rated limit of the component. Additionally, the worst case component temperatures should not exceed the rated limits. NAVMAT 4855-1. (Ref. 43)

3. Verify that the transformer and inductor coils are not in saturation during peak load and transient conditions. STARTUP TRANSIENTS IN SWITCHING REGULATORS (Ref.28), NAVMAT 4855-1 (Ref. 43)

4. Compare the specified voltage, frequency and thermal rating of insulation to the applied levels and assess with respect to life degradation. Insulation resistance degrades inversely with temperature, applied voltage, frequency (or polarity reversals). Figures 31 and 32 represent the life degradations associated with the first two environmental influences. The term MIL in Figure 32 means .001 inch. Figure 33 represents voltage derating necessary to avoid insulation breakdown as a function of frequency. Figure 31 is representative of Kapton (Trademark EI DuPont de Nemours & Co., Wilmington, DE) insulation. Figures 32 and 33 are representative of insulation in general, ie., epoxies, silicones, polyurethanes, etc. Information in Reference 29 was extracted from the Wright Patterson AFB Avionics Systems Division's report AFWAL TR-88-4143 entitled "Designing Guidelines: Designing and Building High Voltage Power Supplies". APPLYING AVIP TO HIGH VOLTAGE POWER SUPPLY DESIGNS (Ref. 29)

5. Require stability, stress and worst case analysis on power supplies. The stress analysis should be supported with measured data from breadboard or engineering models since the current and voltage wave forms induced

during switching action are difficult to calculate accurately. MCDONNELL DOUGLAS ELECTRONICS SYSTEMS COMPANY

6. A thorough vibrational analysis should be required on all large and heavy components installed in the power supply to determine if the leads are capable of supporting the component during operational maneuvers. This will minimize the number of components with failed leads by allowing the designer to provide alternate support for the components.

7. Qualification and reliability development test requirements should be expanded to include subjecting power supplies to specified transient conditions and verifying satisfactory performance. MCDONNELL AIRCRAFT COMPANY

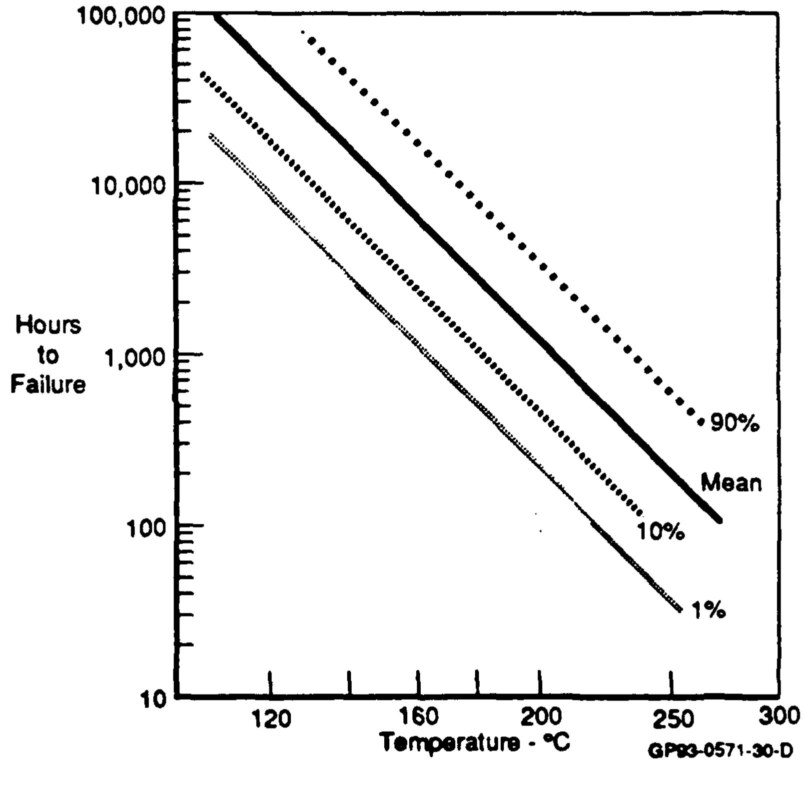


Figure 31. Temperature Dependence of Insulation Life

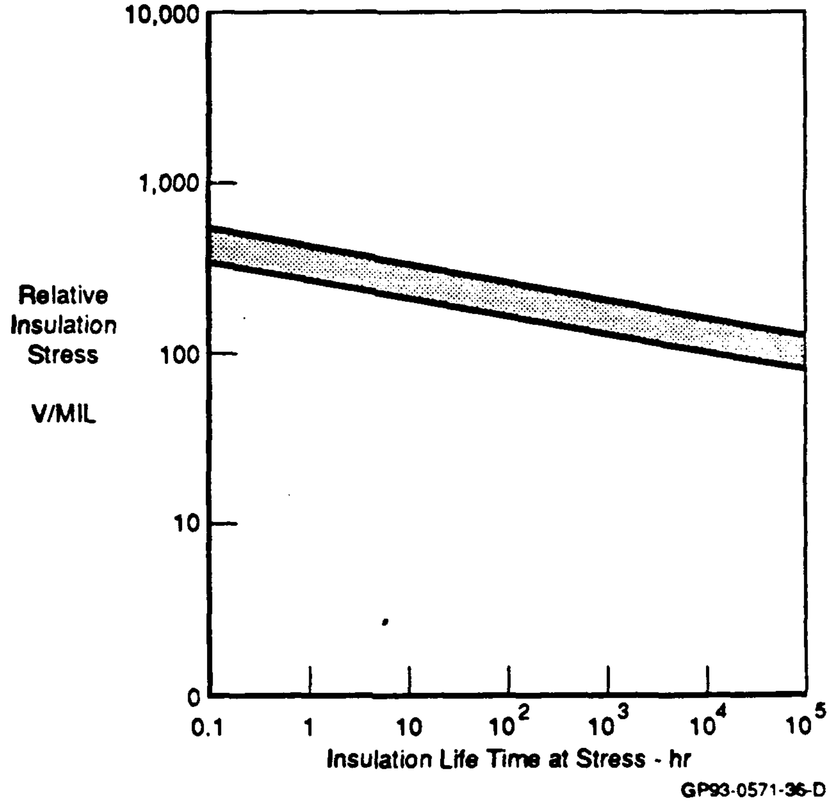


Figure 32. Voltage Dependence of Insulation Life

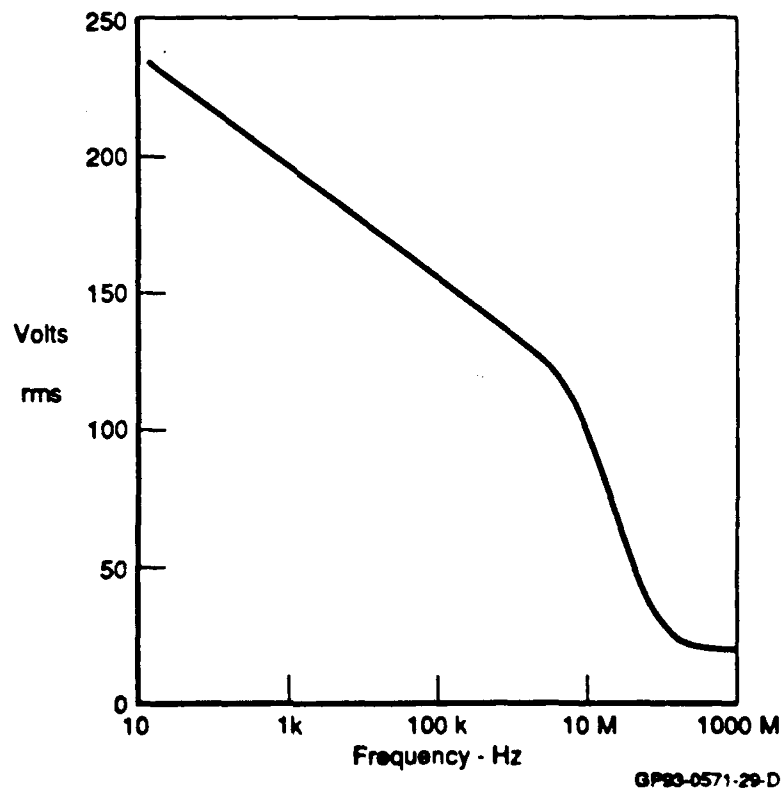


Figure 33. Insulation Voltage Rating Dependence on Frequency

Chapter 3

Avionics Selection

3.0 Introduction

Task 3 of the statement of work required MCAIR to select twenty pieces of avionics from the equipment list of the Air Force's JOINT STARS program as the subjects of this study. It was stipulated that the equipment selected must be currently installed on an operational airborne platform for which field failure data was available. Furthermore, the chosen equipment was to be representative of various applications such as radar, navigation, communication, digital computers, etc. Once the equipment was selected, detailed engineering and failure data was to be collected. This data included input/output specifications, predicted failure rates, schematics, field failure data and operating hours. Field failure data was collected from the Air Force's 66-1 system and the Navy's 3-M data system.

In order to accomplish this task, support was required from Rome Air Development Center (RADC). First, RADC was to supply MCAIR with the JOINT STARS equipment list. Secondly, once the equipment was chosen, RADC would supply MCAIR with the name of the equipment manufacturer and the equipment engineer's names within the JOINT STARS program office.

3.1 Selection Process

MCAIR began this task by initiating a request for D056E and G033B data for the E-3A/B/C (AWACS) aircraft since it was believed that much of the JOINT STARS equipment was present in the AWACS platform. AFLC/MMDA complied with our request and supplied MCAIR with two years of data. This complemented information MCAIR already had on the F-4, B-52, A-7, FB-111, A-10, F-15, F/A-18, AV-8 and F-16.

Once MCAIR obtained the Logistics Support Analysis Control Number List (equipment list) for the JOINT STARS program, identification of potential avionics for the study began. Seventy-seven power supplies were identified as line items within this publication. These power supplies were then cross referenced with the Avionics Planning Baseline (APB) document (ASD-TR-88-5026) published by ASD-AFAL/AXP out of Wright Patterson AFB. The APB lists the nomenclature (eg. ARC-173, ASN-119) of all of the avionics which are used in the Air Force. It then cross references the avionics to the platforms where it is installed. Unfortunately, none of the equipment on the JOINT STARS platform cross referenced to any other platform in the operational Air Force. The attempt to select JOINT STARS equipment was terminated with RADC's concurrence.

It was then decided to select ten pieces of avionics from both the E-3

Nomenclature	Work Unit Code
Flight Control Computer	57D91YO/ZO
RT 1250 Receiver/Transmitter	62X2150
Inertial Navigation Set	73M18FO/GO/HO
Horizontal Situation Display	
Low Voltage	73X32YO
High Voltage	73X32XO
Radar Receiver/Transmitter	
High Voltage	742G120
DC-DC Converter	742G150
Switching Regulator	742G180
Radar Computer Power Supply	
DC-DC Converter	742G410
Linear Regulator	742G420
Radar Target Data Processor	
DC-DC Converter	742G3NO
Linear Regulator	742G3MO
Multipurpose Display Indicator	
Low Voltage	74681MO
High Voltage	74681NO

Table 2. Selected Power Supplies

(AWACS) and the F/A-18 platforms. A candidate list of thirty-two power supplies from the E-3 was submitted to RADC for approval. Subsequently, contact was made with Tinker Air Force Base (AFB) to determine if they would be able to provide the support necessary to gather the engineering data. The required engineering data was not available; therefore, RADC decided to proceed with avionics equipment from the F/A-18 only since the data was readily available at MCAIR, the prime contractor for the airplane. The equipment chosen is listed in Table 2. Additional information on this equipment is located in Appendix D.

3.2 Data Collection

Subsequent to selecting the power supplies for the study, the process of collecting failure data, operating hours and engineering documents began. Failure data was collected for a five year period spanning 1984 through 1988 during which the F/A-18 incurred approximately 500,000 flight hours. The data was collected from the Navy's 3-M data system. This system is used to collect maintenance and operational data for Navy weapon systems. Three basic failure reports were processed for this study:

1) The piece part summary which provides a detailed list of every part which was replaced on a given circuit board/shop replaceable assembly (SRA). This data is taken from the H-Z records of the 3-M data system. The H-Z records provide data on identification of failed parts associated with any maintenance action. The part number, reference designator and the number of parts replaced are included.

2) The SRA replacement summary provides a detailed list of the power supplies which were removed from the aircraft. The report identifies the power supply by work unit code and part number. Information includes the total number of SRAs removed and how many of these removals fall under each of the general failure classifications (defective, can-not-duplicate, cannibalization, other). This information is processed from the E records of the 3-M data system.

3) The failure mode analysis report which categorizes power supply removals by the malfunction code recorded at the time of removal. This report includes the work unit code, the malfunction code and the number of removals charged against the malfunction code.

Several iterations were necessary before acceptable data was available. During the initial data analysis, numerous duplicate records were discovered resulting in inflated failure rates. Data analysis programs were modified to eliminate these duplicate records and the analyses continued without further trouble.

Engineering data was collected concurrently with the failure information. Schematics of the power supplies, block diagrams, detailed MIL-HDBK-217 reliability predictions, procurement specifications and intermediate level maintenance technical publications were acquired. The reliability predictions were all done to MIL-HDBK-217B or C during the full scale development period of the F/A-18. These predictions were based on calculated stresses and represent the series failure rate - they do not represent a mission failure rate. These predictions were accepted by MCAIR and Navy reliability engineers as technically accurate; therefore, the technical accuracy of the predictions were not investigated or questioned for the purposes of this study.

Chapter 4
Electrical Interface

4.0 Introduction

The fourth task of this study was to evaluate the input power requirements of the avionics chosen for this study. The information collected serves two purposes. First, it provides the specified electrical input requirements to which the equipment was functionally designed which allowed us to determine if power supply designs are compatible with the supplied input power. Second, it provides a means to determine if differing input power qualities can effect the reliability of the power supplies, ie., was a more reliable piece of avionics subjected to a more benign environment than a less reliable piece of hardware. Table 3 summarizes the electrical interface requirements of the equipment.

4.1 Interface Control Standards

Figure 34 illustrates the general requirements flow (ie., MIL-E-5400 (General Specification for Aerospace Electronic Equipment)) calls out MIL-STD-454 (Standard General Requirements for Electronic Equipment) which in turn calls out MIL-STD-704 (Aircraft Electrical Power Characteristics) and the pertinent paragraphs which apply to avionics electrical power supplies. Pertinent paragraphs are not identified for MIL-STD-704 since the entire document is applicable. All of the major equipments called out MIL-E-5400 paragraph 3.2.23 as the requirement for input power with the exception of the ARC-182 communication set. MIL-E-5400 in turn calls out Requirement 25 of MIL-STD-454 as the governing document. Finally, Requirement 25 calls out MIL-STD-704 as the governing document for airborne equipment. The procurement specifications then further refined the requirement to encompass MIL-STD-704 Category B. The ARC-182 Communication Set simply calls out MIL-STD-704.

4.2 MIL-STD Requirements

MIL-STD-704 defines overvoltage as a voltage which "... exceeds the combined steady state and transient limits for normal operation and is limited by the action of protective devices." Figure 35 illustrates the overvoltage limits for AC voltages and Figure 36 illustrates the

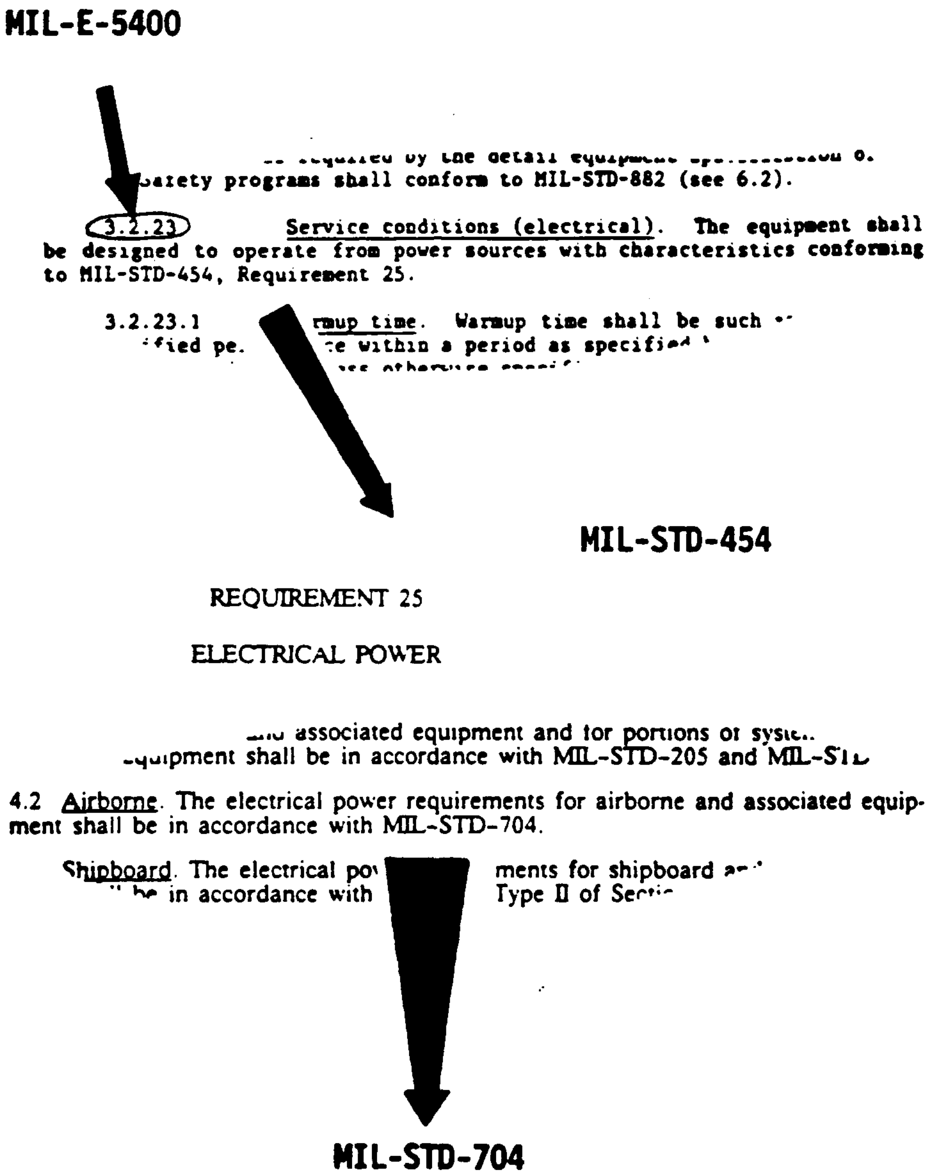


Figure 34. Electrical Power Interface Specifications

overvoltage limits for DC voltages. The MIL-STD does not in turn define the term transient, but it is interpreted to be the voltage limits and

Equipment	Specification	Input Power Requirements	Power Requirements	Transient Susceptibility
Horizontal Situation Indicator	74-870078	MIL-E-5400 para. 3.2.23 MIL-STD-704 Category B	115/200 VAC, 440 VA 0-5 VAC, 10 VA	No degradation with each interface cabled bundled with a wire conducting a relay minimum switching transient of +/-600 volts peak.
Flight Control Set	74-870086	MIL-E-5400 para. 3.2.23 MIL-STD-704 Category B	28 VDC 1300 W max @ 30 VDC	No degradation with each interface cable bundled with a wire conducting a relay minimum switching transient of +/-600 volts peak.
Radar	78-870052	MIL-E-5400 para. 3.2.23 MIL-STD-704 Category B	115/200 VAC 5450 VA, XMTR 450 VA, remainder 28 VDC 400 W, antenna drive 200 W. remainder	No degradation with each interface cabled bundled with a wire conducting a relay minimum switching transient of +/-600 volts peak.
Multipurpose Display Indicator	74-870074	MIL-E-5400 para. 3.2.23 MIL-STD-704 Category B	115/200 VAC, 0-5 VAC, 10 VA max	No degradation with each interface cable bundled with a wire conducting a relay minimum switching transient of +/-600 volts peak.
ARC-182/ RT-1250	MIL-R-85664(AS)	MIL-STD-704	28 VDC, 150 W max	Not Specified
INS	PS 74-870082	MIL-E-5400 para. 3.2.23 MIL-STD-704 Category B	115 VAC, 1650 VA (warm up) 115 VAC, 250 VA (normal) 28 VAC, 20 VA	No degradation with each interface cable bundled with a wire conducting a relay minimum switching transient of +/-600 volts peak.

Table 3. Electrical Interface Requirements

ity	Spike Emission	Overload Protection	Lightning Requirements
rface cablod g a relay f +/-600 volts	Spikes (transients >500 micro-seconds) shall not exceed the following values when measured from the base of the transient: a) 28VDC, +14/42V b) 115VAC +/-60V	Equipment must meet the requirements of para. 3.2.20 of MIL-E-5400 except as noted: a) No permanent damage shall be sustained by the power supply due to any transient external to the WRA. b) Equipment shall not sustain chain reaction failures. Fuses and similar devices shall not be used without permission.	Not Specified
rface cable g a relay f +/-600 volts	Spikes (transients >500 micro-seconds) shall not exceed the following values when measured from the base of the transient:. a) 28VDC, +14/42V b) 115VAC +/-60V	Equipment must meet the requirements of para. 3.2.20 of MIL-E-5400 except as noted: a) No permanent damage shall be sustained by the power supply due to any transient external to the WRA. b) Equipment shall not sustain chain reaction failures. Fuses and similar devices shall not be used without permission.	Each flight critical interface wire shall withstand a 5000V peak double exponential pulse of either polarity as follows: $E=+/-Ae^{-bt}-{}^{-dt}$ b = 1.4E4 d = 3.6E6 A = 510 Z (source) = 100 ohms Protection devices must have nanosecond response times.
rface cabled g a relay f +/-600 volts	Spikes (transients >500 micro-seconds) shall not exceed the following values when measured from the base of the transient: a) 28VDC, +14/42V b) 115VAC +/-60V	Equipment must meet the requirements of para. 3.2.20 of MIL-E-5400 except as noted: a) No permanent damage shall be sustained by the power supply due to any transient external to the WRA. b) Equipment shall not sustain chain reaction failures. Fuses and similar devices shall not be used without permission.	
face cable g a relay +/-600 volts	Spikes (transients >500 micro-seconds) shall not exceed the following values when measured from the base of the transient: a) 28VDC, +14/42V b) 115VAC +/-60V	Equipment must meet the requirements of para. 3.2.20 of MIL-E-5400 except as noted: a) No permanent damage shall be sustained by the power supply due to any transient external to the WRA. b) Equipment shall not sustain chain reaction failures. Fuses and similar devices shall not be used without permission. c) I/O Devices must be able to withstand the following waveform: 3000 Vpeak, 1-3 nanosecond pulse, 500mA d)Arc suppressors shall be used to preclude damage to components from HVPS and HV CRT arcs.	Not Specified
	Not Specified	a) Unit shall not be damaged by voltages less than those allowed by 704. b) Reverse polarity shall not dmaage the XMTR/RCVR.	Not Specified
face cable a relay +/-600 volts	Spikes (transients >500 micro-seconds) shall not exceed the following values when measured from the base of the transient: a) 28VDC, +14/42V b) 115VAC +/-60V	Equipment must meet the requirements of para. 3.2.20 of MIL-E-5400 except as noted: a) No permanent damage shall be sustained by the power supply due to any transient external to the WRA. b) Equipment shall not sustain chain reaction failures. Fuses and similar devices shall not be used without permission.	Not Specified

durations which the equipment must operate through without malfunction. These limits are illustrated in Figure 37 (AC voltages) and Figure 38 (DC voltages). MIL-E-6051, referenced in the figures, defines System Electromagnetic Compatibility Requirements. The standard fails to define the maximum transient the equipment must be able to withstand without degradation. It simply states at what voltage level protection devices must begin to protect the equipment and at what voltages the equipment must continue to operate normally. The definition of a wave shape to be used as representative of the environment is important for the design of protective

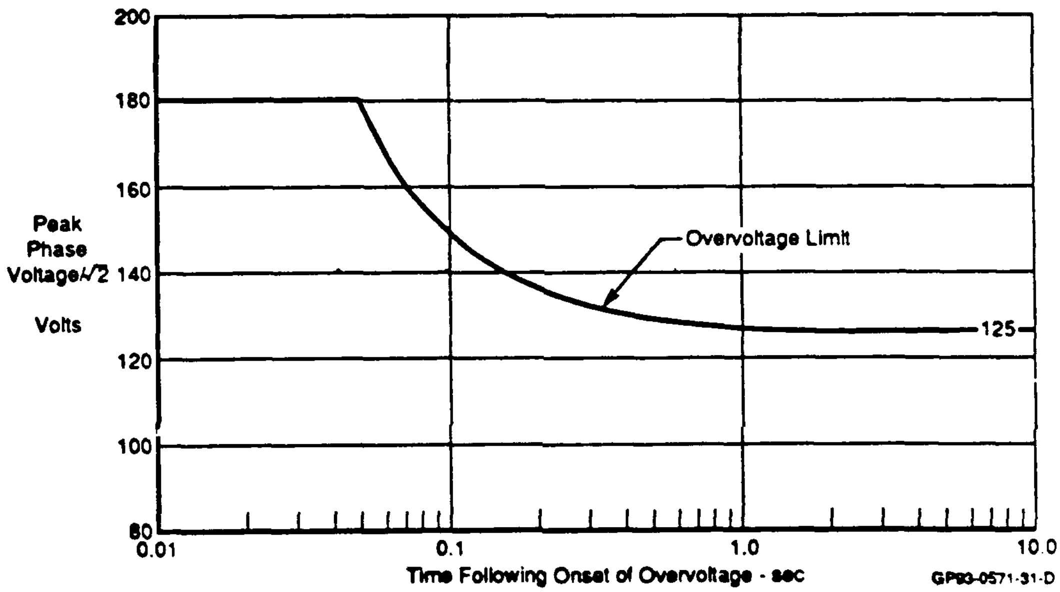


Figure 35. AC Overvoltage Limits

devices since unrealistic requirements, such as excessive duration of the voltage or very low source impedance, place a high energy requirement on the suppressor with a resulting cost, weight and volume penalty. A complete specification should include the maximum voltage transients which may appear, the voltage waveform and the overvoltage source impedance.

4.3 Procurement Specification Requirements

The transient susceptibility requirement of Table 3 is similar in that it calls out a requirement that the equipment must function normally when interface wiring is subjected to coupled transients emanating from a wire with 600V peak to peak transients, but does not call out the levels the equipment must protect itself from. The spike emission requirement defines the maximum voltage levels of electromagnetic interference that can be broadcast onto the power bus by the equipment.

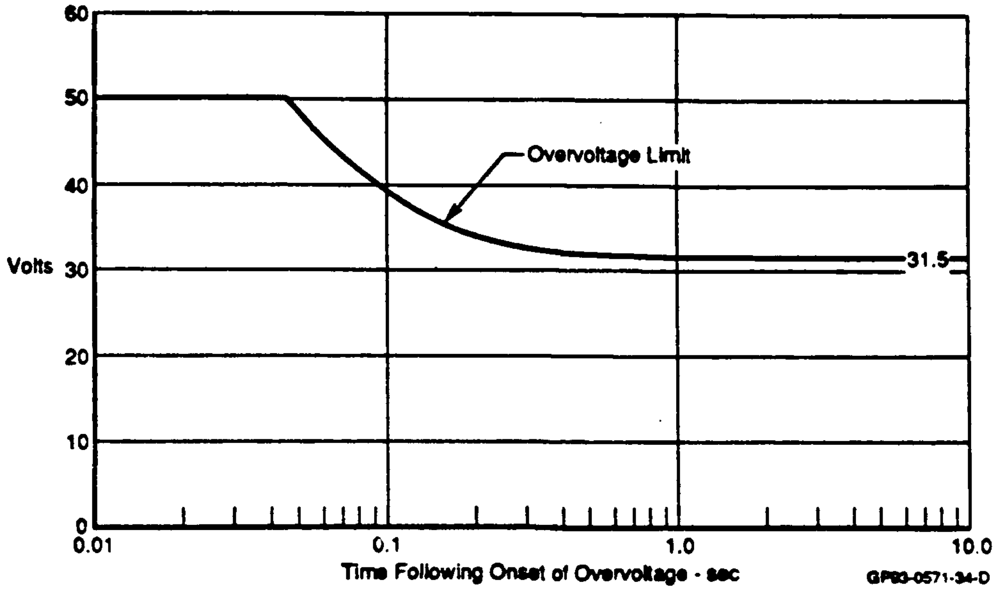


Figure 36. DC Overvoltage Limits

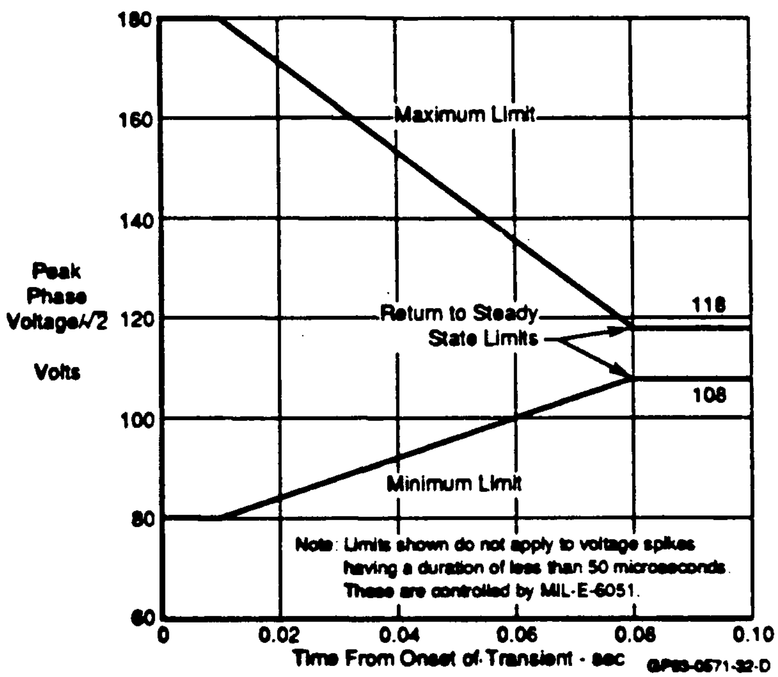


Figure 37. AC Transient Limits

The overload requirement of the procurement specification calls out paragraph 3.2.20 of MIL-E-5400 which then calls out Requirement 8 of MIL-STD-454. Requirement 8 specifies (for Class 2 equipment) that current overload protection shall be provided via circuit breakers or fuses to avoid the hazards of fire, smoke, explosion or arc over. The procurement specifications add some meat to this requirement by stipulating that no permanent damage may be sustained by the power supply due to any transient external to the avionics box. Furthermore, equipment can not sustain chain reaction failures due to transient conditions, ie., the failure of one component shall not in turn cause the failure of another component. Only one piece of equipment (the Multipurpose Display Indicator) actually defined a voltage waveform that the equipments' input/output lines must be capable of withstanding without failure. The requirement called out the peak voltage, the peak current and the transient duration. It did not, however, define the waveform in terms of rise time or fall time and it did not describe the transient as a square wave, sine wave, exponentially decaying, etc. A comprehensive requirement needs to have all of these parameters specified.

The final column of Table 3 contains the lightning requirements the

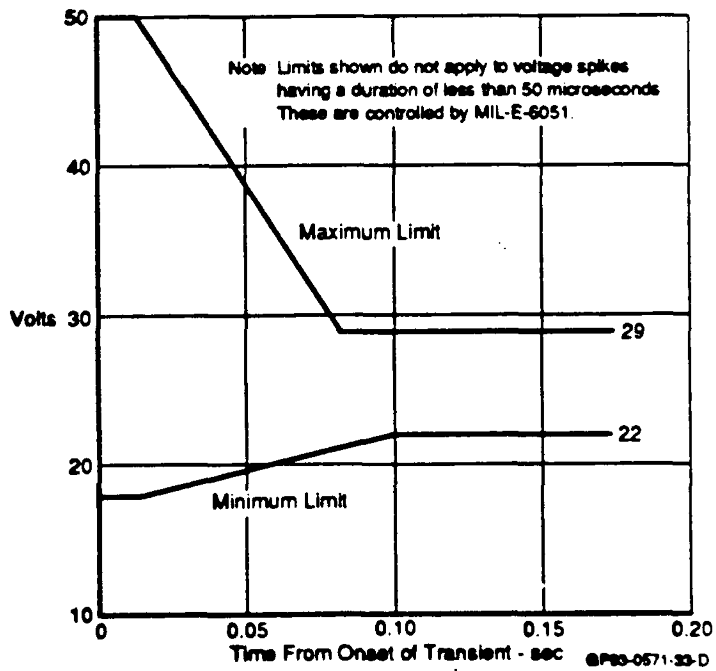


Figure 38. DC Transient Limits

equipment must withstand in terms of waveform, maximum voltage, maximum current and source impedance. Only one piece of equipment (the Flight Control Computer) had this requirement levied against it. Although this requirement is better than nothing, it is not as stringent as the IEEE waveforms for lightning induced transients discussed in Chapter 1.

4.4 Summary

Overall, the equipment in this study was basically designed to the same requirements. It is not likely that differences in power supply reliability are due to the small variations in the power specifications.

Chapter 5

Power Supply Failure Modes

5.0 Introduction

Task 5 of the statement of work required the identification of the failure modes of power supplies. This was to be accomplished by reviewing the failure data collected for the other analyses, reviewing historical F/A-18 test data and evaluating the How-Mal codes of power supply failures.

A historical view of power supply failure modes was obtained by reviewing the F/A-18 Reliability Development Test (RDT) Summary Report. This report covered tests conducted between 1979 and 1984. Many of the failures that appear in RDT are the result of unique circuit interactions which are very difficult to determine analytically, while some could be eliminated with timely common sense engineering practices. Hopefully, lessons can be learned from this historical data base and applied to future designs, minimizing redesign effort and costs.

5.1 Failure Modes

5.1.1 Wiring Failures

Wiring failures were reported more frequently than any other failure type. Failures included broken wires, chaffed wires, pinched wires, improperly routed wires, etc. This abundance of wiring problems is associated with the above average use of point to point wiring in power supplies instead of the more common use of printed circuitry as in other electronics. While wiring can not be avoided altogether, problems can be minimized. As stated in the design guidelines section, flex print circuitry should be used whenever possible so routing will be more consistent. Very precise wire routing, tie down locations and bend radii should be specified in the manufacturing instructions. While not wanting to state the obvious, the obvious is overlooked far too frequently to ignore. Whenever possible, route wiring in any manner to avoid wrapping the wire over a sharp edge. Invariably, if the opportunities are there, a technician will wrap the wire too tightly over the edge and failure will result. One other "obvious" failure mode turned up several times in the RDT report involving the use of solid core wire. This type of wire is less flexible and more subject to fatigue cracking than stranded wiring. Stranded wiring should be the only wire type considered for use in avionics.

5.1.2 Broken Component Leads

The second most common failure reported involved broken component leads of power supply components. The leads were always associated with large, heavy components typical to power supply designs such as transformers, inductors and capacitors. These components must be mounted very securely to the chassis or circuit board by some means other than the component leads. Mounting can be established via a mechanical means such as screws or clamps and by bonding. The components are too heavy for the leads to withstand the vibrational forces. Prudent designs will allow for this prior to the time when test and operational failures mandate a redesign.

5.1.3 Coil Windings

Transformers and inductors suffered from numerous winding failures at the interface with lead wires. These very fine wires can not withstand much stress at all, either from vibration or temperature induced expansion and contraction. Some form of stress relief must be incorporated into the interface to eliminate this problem. Incorporating inductor and transformer design and manufacturing techniques which have been proven in the field is the best solution to this problem.

5.1.4 Intermittent Electrical Connections

Mechanical attachment points (nuts and bolts) which also provide the electrical interface were reported as failures several times. Two problems exist with this type of design. First, vibration and thermal expansion work together to loosen the attaching hardware which leads to electrical discontinuities and poor thermal paths. Using material with similar thermal coefficients of expansion will minimize the thermal aspects of this problem. The vibration problem is generally minimized by the use of locking nuts, torque values and Loctite TM. This in turn becomes a quality problem to ensure the proper nut is used, the nut has been torqued and the Loctite TM has been applied. Secondly, conformal coating material has a nasty habit of covering the mating surfaces of these electrical contacts if they are not properly masked. It is also capable of flowing between the mating surfaces of previously assembled hardware. Both of these situations lead to intermittent electrical opens which cause power supply failures.

5.1.5 Input Circuitry

As mentioned in Chapter 1 and 2, soft start circuity should be designed into the supply form the beginning. One supplier realized this too late and had to incorporate the circuitry since the input filters were blowing repetitively.

5.1.6 Drive Transistors

Finally, the drive transistors were the source of numerous failures both in RDT and operationally among the various equipment. Causes of these failures were numerous. One redesign was initiated because of the large charge storage in the transistor. This storage would delay the transistor from turning off resulting in increased power dissipation. Chapter 1 discusses this problem in more detail. Several redesigns were initiated due to current imbalances in parallel drive transistors. This imbalance can cause one transistor to warm to the point where its resistance begins to decrease, allowing thermal runaway to begin. This problem can be eliminated by using matched pair transistors mounted on the same thermal plane or with other techniques suitable for obtaining a balanced current flow. One other problem was related to both transistors and wiring. Transistors were failing due to excess parasitic capacitance in the wiring leading from the transistor. This capacitance could alter switching waveforms resulting in overheated junctions. Additionally, the extra capacitance will draw extra current when the transistors are switched on. Altering the wiring length and routing solved this problem. While the use of flex print may not have eliminated this problem initially, it will keep the problem from appearing randomly throughout production due to inconsistent wiring practices.

Drive transistors have also been known to fail due to inattention to the core saturation tendencies of power inverter transformers. When a core goes into saturation (defined as the point where an increase in magnetizing current no longer causes an increase in flux) based upon a given voltage impressed across it, the current spikes since the inductor can no longer inhibit the rate of current rise. This problem is caused by misapplication of the transformer, ie. the transformer is too small, or by an unbalanced drive volt-second product across the transformer. To remedy this problem, the designer can select a core with higher saturation limits or ensure the drive is balanced. An explanation of this problem follows.

First, a balanced drive is obtained when the volt-second product of the positive and negative drive pulses are equal, ie., the area of the pulses on each side of the time axis are equal. Figure 39a illustrates a balanced drive and Figure 39b illustrates an unbalanced drive. Second, transformers

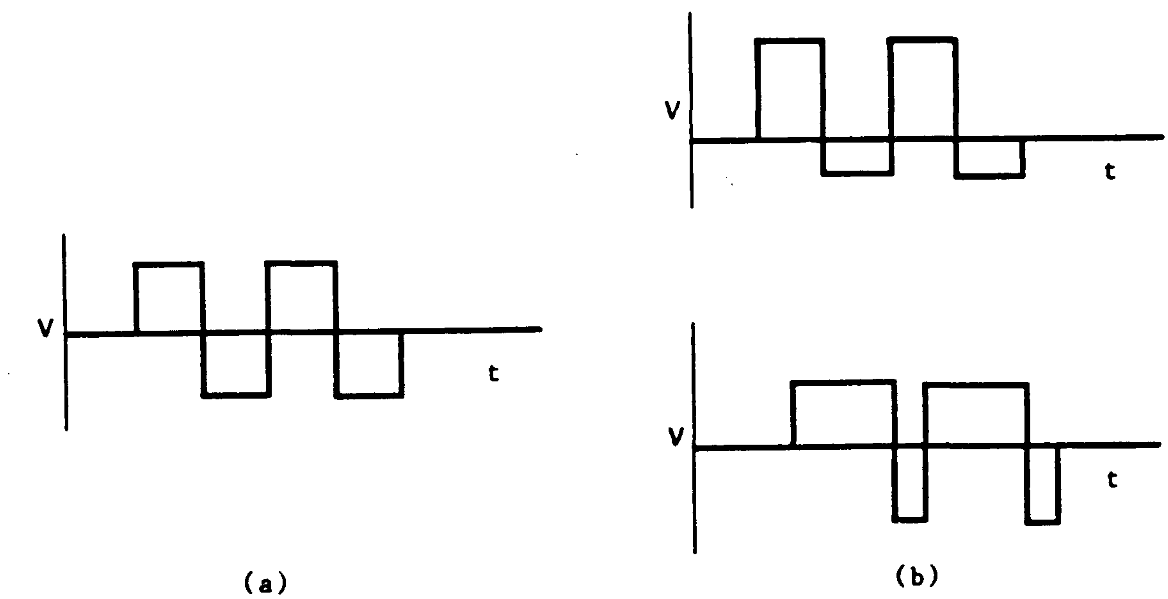


Figure 39. Balanced & Unbalanced Volt-Second Products

are usually selected to have a square hysteresis loop as shown in Figure 40a. When driven by a balanced drive, the properly selected transformer will have a square hysteresis loop which is smaller (see Figure 40b) than the maximum loop specified. Even with a balanced drive, a core will saturate and cause problems if not selected properly for the application. An unbalanced drive will have the effect of shifting the hysteresis loop up (or down) on the magnetic flux density axis as shown in Figure 41. As illustrated, the hysteresis loop has been shifted to the point where the flux density can no longer be increased, identifiable by the large tail on the top of the loop. When this happens, as explained earlier, the flux can no longer inhibit current rise and a current spike results as illustrated in Figure 42. If transistors are used to switch the drive waveform, the high current allowed by the saturated core will pass through the transistor and cause it to exceed its safe operating area (SOA) curves resulting in excessive junction temperatures. Degradation and eventual failure will result.

5.2 "How - Mal" Analyses

The How-Mal (how malfunction) codes analyzed from the Navy's 3-M system analysis did not yield any useable results. The codes were sorted by power supply and plotted, but the codes recorded were not beneficial in determining failure modes of power supplies. The typical How-Mal code used translated to "Fails - Diagnostic/Automatic Test", "No Output", or "Voltage Incorrect". This effort was subsequently terminated.

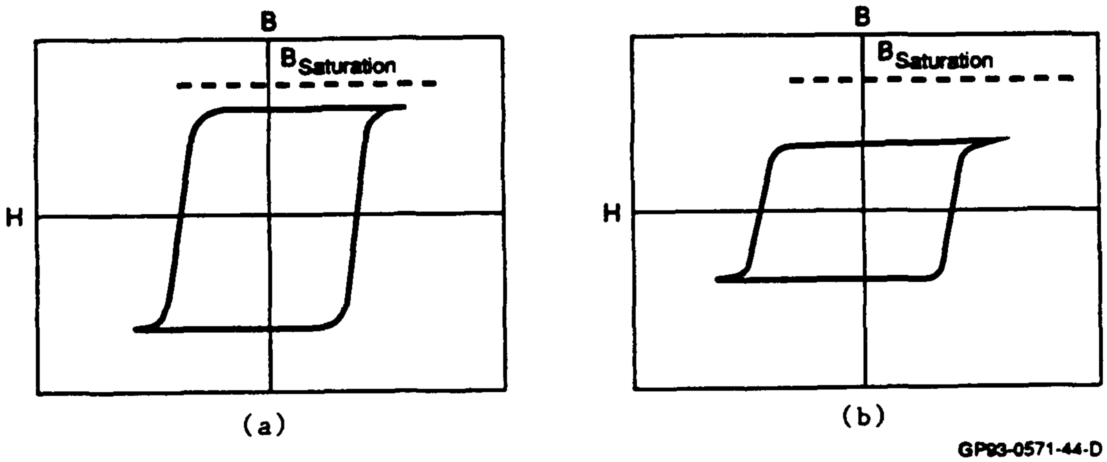


Figure 40. Hysteresis Loop - Balanced

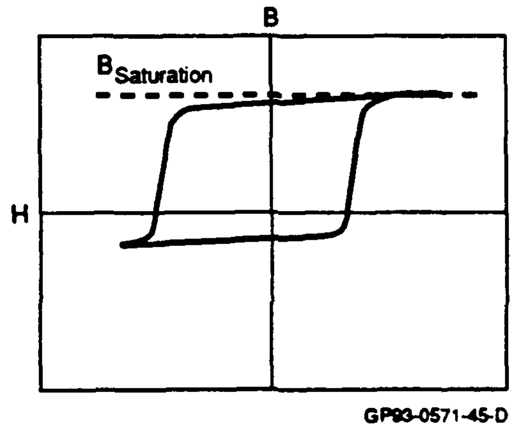


Figure 41. Hysteresis Loop - Unbalanced

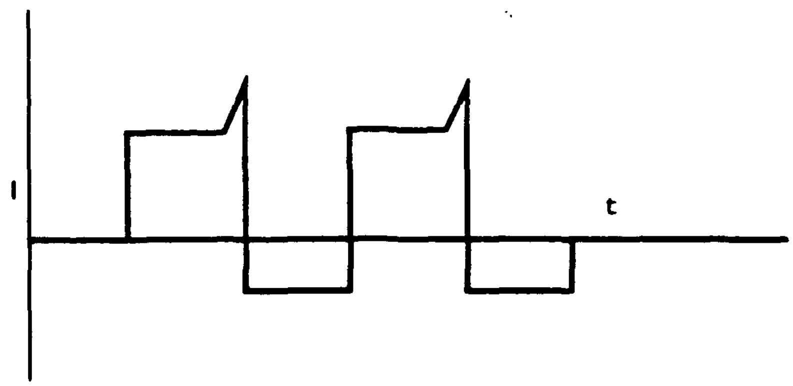


Figure 42. Current Spiking from Unbalanced Hysteresis

Chapter 6

Data Analyses

6.0 Introduction

Task 6 of the statement of work required MCAIR to analyze the collected operational field data and design data to determine any relationships which may exist between unique design parameters and the field reliability of power supplies. Specifically, the relationships which needed to be determined include:

a) The relationship between the operational reliability and the predicted reliability of power supplies.
b) The relationship between power supply reliability and the reliability of other electronics housed within the same box as the power supply.
c) The relationship between power supply reliability and overall complexity.
d) The relationship between total part failures and protection part failures.
e) The relationship between reliability and transient protection complexity.
f) The relationship between power supply type and reliability.

The following paragraphs will explain the methodology used to determine these relationships, the reason they were needed and the results of the analyses.

Several terms have been used in this chapter which should be defined. The achieved failure rate (FR) is defined as the ratio of the operational failure rate to the predicted failure rate. This ratio was used so power supplies with widely varying predictions and field performance levels could be compared together. Additionally, the ratio was necessary for predicted failure rates, operational failure rates and various other parameters to be compared together in one chart. The acronym WRA (weapons replaceable assembly) is a Navy term used for avionics boxes and is equivalent to the Air Force term LRU (Line Replaceable Unit). The acronym SRA (shop replaceable assembly), equivalent to Air Forces' SRU (Shop Replaceable Unit), is the Navy term for circuit boards or modules removable from a WRA.

6.1 Power Supply Operational vs Predicted Reliability

The first analysis of the field data was intended to determine how well the power supplies performed operationally with respect to their predicted reliability. Also, with the way Figure 43 is plotted, one can compare the ratio of operational to predicted failure rate as a function of complexity since units with a higher predicted failure rate are generally more complex. To this end, the operational failure rate was plotted against the predicted failure rate as illustrated in Figure 43.

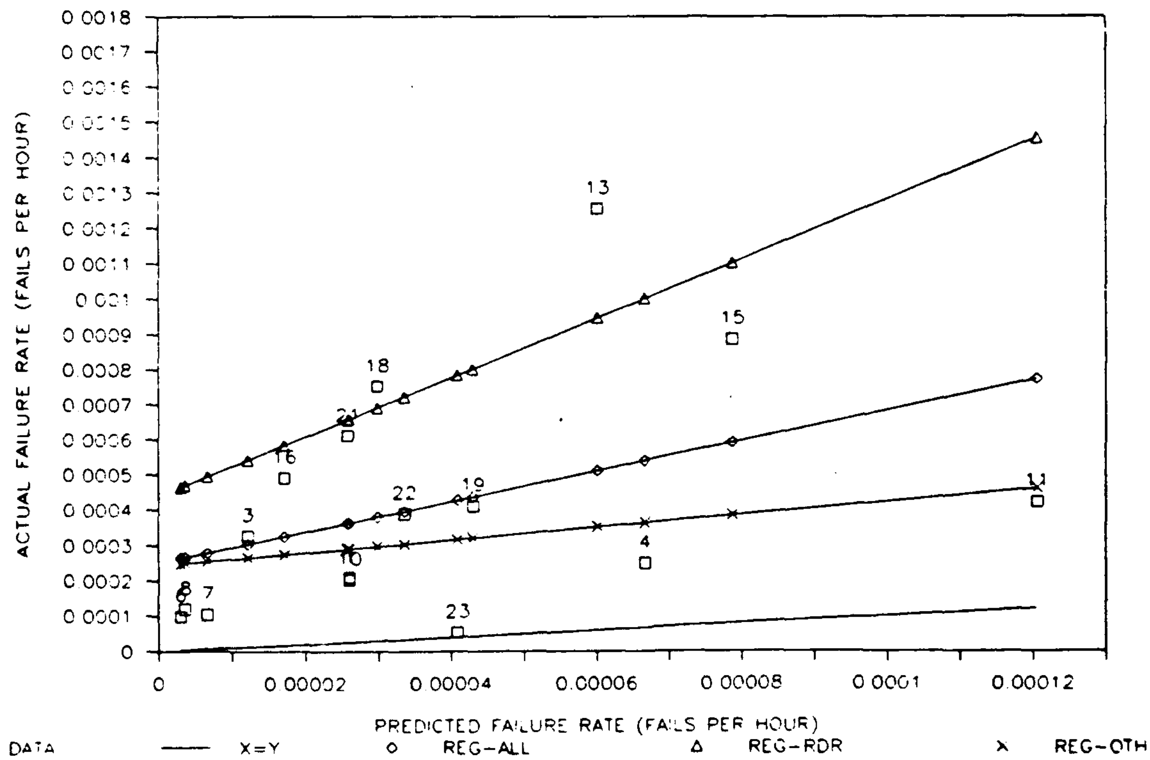


Figure 43. Predicted Power Supply Failure Rate vs Actual

This figure includes data points for each power supply SRA which was part of this study. Table 4 contains a list of these power supplies and their respective identifying number used in the following graphs. The line X-Y represents the plot obtained when the operational failure rate is set equal to the predicted failure rate. There are three regression lines plotted on the graph. REG-ALL represents the regression obtained when all SRA data points are considered together. REG-RDR represents the line obtained when only radar SRA data points (13,15,16) are considered. Finally, REG-OTH represents the line obtained when all other SRAs besides the radar SRAs were considered.

Identifying Number	Nomenclature
1	Flight Control Computer Low Voltage Supply
2	Multipurpose Display Indicator (MDI) Total (3&4)
3	MDI Low Voltage Supply
4	MDI High Voltage Supply
5	Inertial Navigation Set (INS) Total (6,7&8)
6	INS Rectifier
7	INS DC-DC Converter
8	INS Sequence Monitor
9	Horizontal Situation Display (HSD) Total (10&11)
10	HSD High Voltage Supply
11	HSD Low Voltage Supply
12	Radar Transmitter Total (13&14)
13	Transmitter High Voltage
14	Transmitter Low Voltage (15&16)
15	Transmitter DC-DC Converter
16	Transmitter Switching Regulator
17	Radar Target Data Processor (RTDP) Low Voltage (18&19)
18	RTDP DC-DC Converter
19	RTDP Linear Regulator
20	Computer Power Supply (CPS) Low Voltage (21&22)
21	CPS DC-DC Converter
22	CPS Linear Regulator
23	RT-1250 Radio Low Voltage Supply

Table 4. Power Supply Identification

The functions to which each line has been plotted are as follows:

X-Y, $y = x$

REG-ALL, $y = 4.33x + .00025$

REG-RDR, $y = 8.43x + .00044$

REG-OTH, $y = 1.81x + .00024$

A test for correlation was performed on the data used for each regression line. None of the three lines passed the test for correlation despite the appearance of correlation for the regression line REG-OTH. Table 5 contains the statistically derived information used to determine correlation. The value r represents the linear correlation coefficient and measures how well the regression line fits the data, with a value of 1 indicating a perfect fit. Additionally, when a value r is based on a random sample from a bivariate normal population, a correlation analysis can be performed to substantiate the correlation determined by the value of r. Using the Fisher Z transformation (Reference 44) where n equals the sample size and r is the linear correlation coefficient,

$$Z = .5 * \sqrt{n-3} * \ln (1+r / 1-r)$$

the null hypothesis (ie. there is no correlation) was tested for each of the regression lines. A confidence level of 95% ($|Z| > 1.96$) was chosen as the criterion for the test. As a result of these tests, a decision was made to accept or reject the null hypothesis for each regression line.

Clearly, all of the SRAs performed at an operational failure rate in excess of their predicted rate, a situation which is not totally surprising. Unfortunately, most SRAs performed substantially worse than they were predicted to. As a final note, the radar SRAs appear to perform much worse than power supplies in other applications.

6.2 Reliability of Power Supplies vs Other Electronics

The previous paragraphs have documented power supply performance as "worse than predicted". The obvious question to ask next would be, "How do the power supplies compare with the rest of the electronics they are housed with?" Answering this question will explain whether the power supplies do perform poorly as a class of electronics or whether they are as just as good as the rest of the electronics. A poor performing power supply coupled with a poor performing electronic box is indicative of a problem such as application, design, environment or manufacturing techniques. A poor performing power supply coupled with a stellar performing box may

Figure		Regression Equation	Samples	r	z	Status
43	REG-ALL	Y= 4.33X + .00025	16	.41	1.57	ACCEPT
	REG-OTH	Y= 1.81X + .00024	13	.27	.88	ACCEPT
	REG-RDR	Y= 8.43X + .00044	3	.7	0.0	ACCEPT
44	REG-ALL	Y=32.05X + 25.31	8	.2	.45	ACCEPT
	REG-OTH	Y=-1.13X + 37.4	7	.36	.75	ACCEPT
45	REGRESSION	Y= .52X + 10.3	8	.13	.29	ACCEPT
46	REGRESSION	Y= .05X + .95	15	.53	2.04	REJECT
47	REGRESSION	Y= .03X + .89	11	.69	2.40	REJECT
48	REG-ALL	Y= .02X - 1.29	8	.61	1.59	ACCEPT
	REG-OTH	Y= .02x - 1.97	7	.89	2.84	REJECT
49	REGRESSION	Y= .42X	14		1.27	ACCEPT
50	REGRESSION	Y= .35X	14	.72	2.98	REJECT
51	REGRESSION	Y= .06X + 15.52	16	.07	.25	ACCEPT
52	REGRESSION	Y= .40X + 7.86	11	.42	1.27	ACCEPT
53	REGRESSION	Y= 2.59X + 3.01	4	.86	1.29	ACCEPT
54	REGRESSION	Y= .38X + 6.85	4	.31	.32	ACCEPT
55	REGRESSION	Y=-1.77X + 73.76	3	.75	0.0	ACCEPT
56	REGRESSION	Y= .36X + 9.91	7	.28	.57	ACCEPT

TABLE 5. STATISTICAL ANALYSES RESULTS

indicate power supplies are not as reliable as other electronics. This assumes that the same manufacturer who designed and built the "other electronics" also built the power supply and applied the same engineering and production techniques to both. If this is the case, there must be some fundamental difference separating power supplies from other electronics. These major differences would include the thermal environment, a noisy electrical environment, the component mix (lots of high power devices) and the performance parameters (high speed switching of large currents and high voltages).

To determine the relative merits of power supplies as compared to their brethren housed in the same box, two figures were developed. Figure 44 compares the predicted failure rate of the power supply as a percentage of the total box (WRA) predicted failure rate (x-axis) to the power supply operational failure rate as a percentage of the total box operational failure rate (y-axis). The power supply SRAs were grouped into functional units for this comparison to eliminate noise on the graph, ie., all failures of power supplies for a given box were combined. The data points for each of the boxes studied were plotted along with the line representing an actual failure rate percentage equal to the predicted percentage (X=Y). A regression line for all data points was not plotted since the points were so widely scattered. On examination, it was discovered that data point #12 belonged to the radar transmitter. Therefore, a regression line REG-OTH, representing the other boxes besides the transmitter, was plotted. The equation of the plotted lines are as follows:

X=Y,	$y =$	x
REG-ALL,	$y =$	$32.05x + 25.31$
REG-OTH,	$y =$	$-1.13x + 37.4$

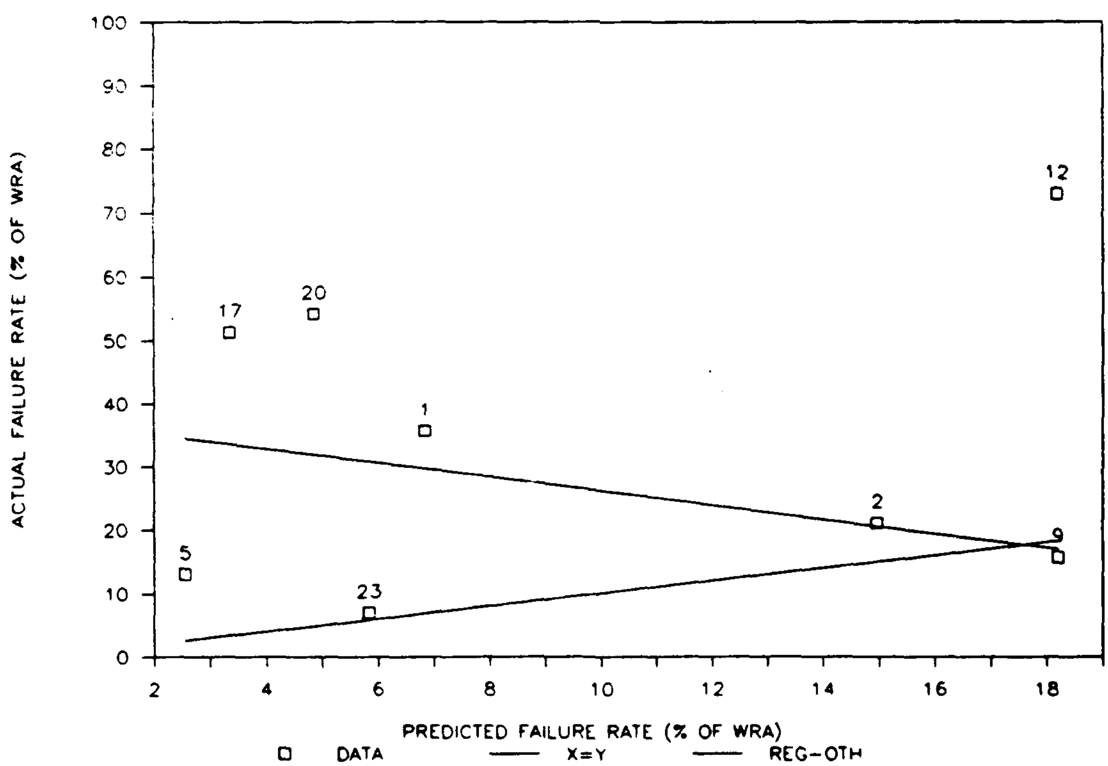


Figure 44. <u>Normalized Predicted Failure Rate vs Actual</u>

The correlation analysis was performed on the regression lines with no success - both lines failed to show correlation analytically.

Figure 44 clearly illustrates the fact that power supplies perform worse than their brethren. Every power supply in the study except one had consumed a higher percentage of total box failures than it was predicted to. As in Figure 43, the radar appears to be performing worse than the rest of the power supplies. However, if the regression line REG-OTH were to continue with the same slope, power supplies with a predicted failure rate greater than 18% of the total box failure rate would theoretically perform as expected.

Figure 45 looks at the data a little differently. It compares a), the ratio of the operational failure rate to the predicted failure rate of the box to b), the ratio of operational failure rate to the predicted failure rate of the power supply. Again, as in Figure 44, 63% of the power supplies achieved a failure rate multiplier much higher than the overall box multiplier, confirming what many have stated as fact for quite some

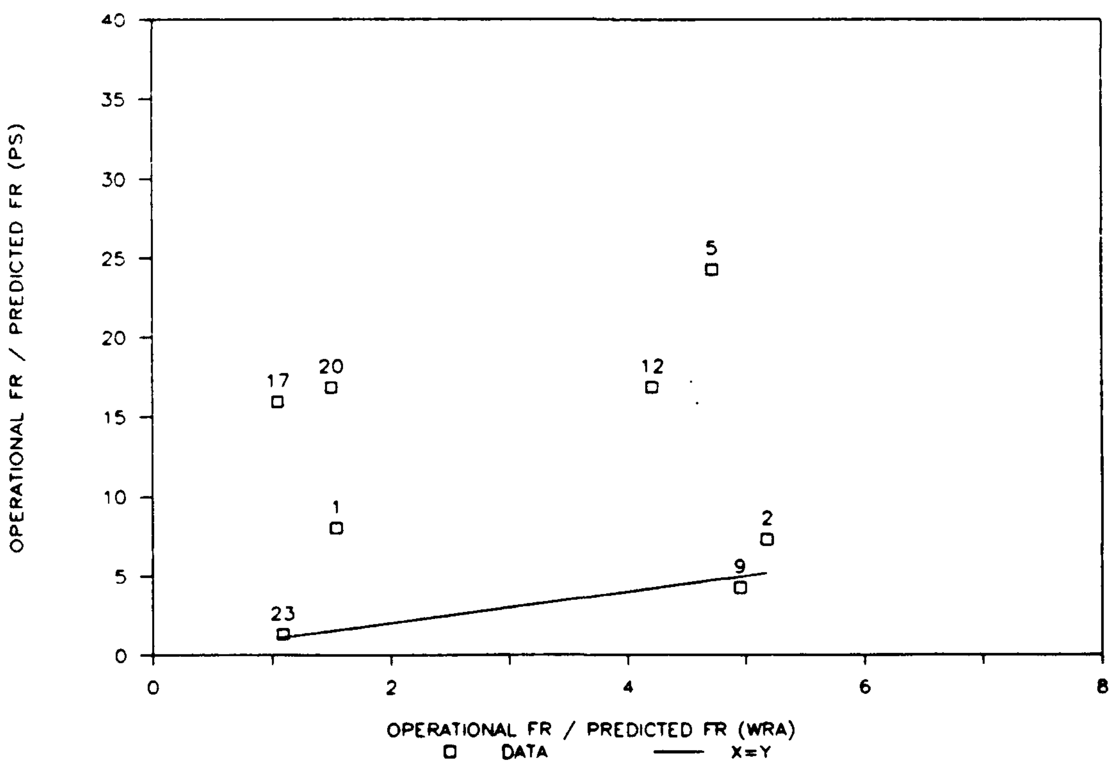


Figure 45.

Predicted Failure Rate Achieved (WRA) vs Predicted Failure Rate Achieved (SRA) time - power supplies are less reliable than other electronic modules. The regression line (not plotted) is represented by the equation:

$$\text{REG}, \qquad y = .52x + 10.3$$

As in Figure 44, the correlation analysis test resulted in a determination of no correlation.

6.3 Power Supply Reliability vs Overall Complexity

The next analysis was performed in an effort to determine if reliability was a function of complexity for the power supplies in this study. To this end, three graphs based on the parts count of the power supplies were generated. The x-axis in these charts represents the total piece part count of the power supply with the achieved failure rate plotted against the y-axis.

The first figure in this set of data (Figure 46) contains data points for all of the SRAs of Table 4. As illustrated, the data is scattered over the

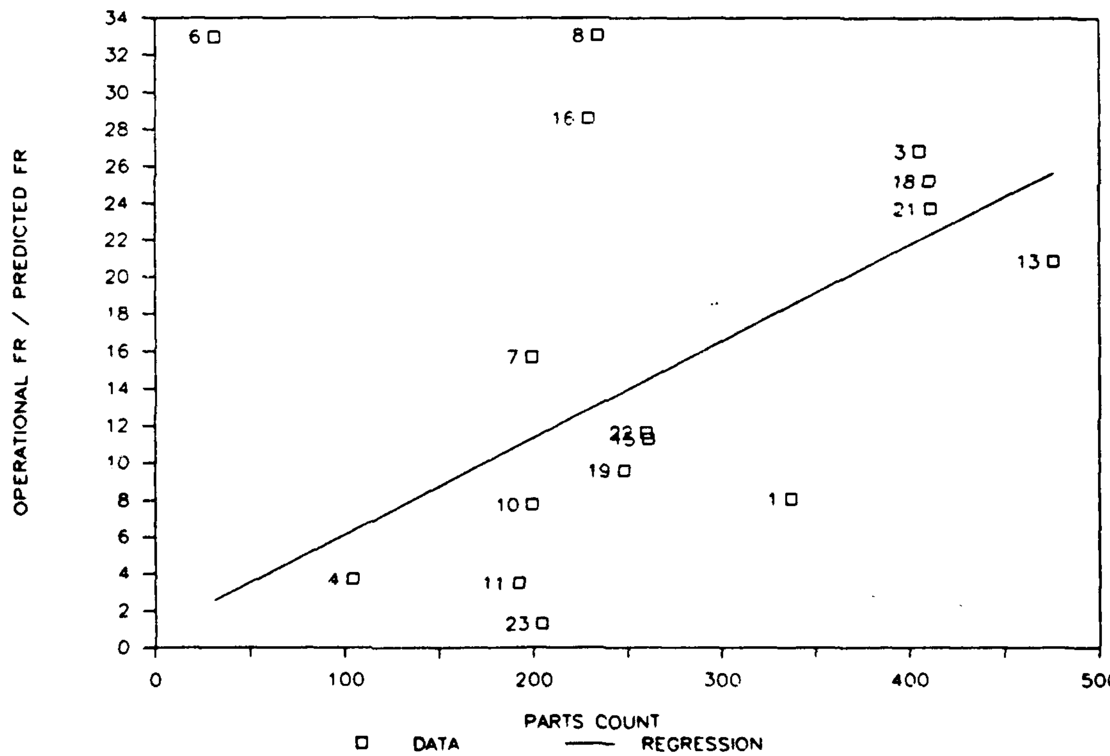


Figure 46. Power Supply Complexity vs Predicted Failure Rate Achieved

entire graph. The regression line was calculated using all of the data points except the one labeled (6), the INS rectifier. This data point has a drastic effect on the regression line and was considered irrelevant because it is not a true power supply SRA; it is a rectifier sub-SRA for a low voltage power supply. The regression line is represented by:

$$\text{REG,} \qquad y = .05x + .95$$

The regression line passed the test for correlation.

In an attempt to eliminate the scatter, the sub-SRAs were grouped to form functional power supplies and the graph was replotted as Figure 47. The scatter was reduced and a regression line with a much better fit than the one of Figure 46 was obtained. The equation of the regression line is:

$$\text{REG,} \qquad y = .031x + .89$$

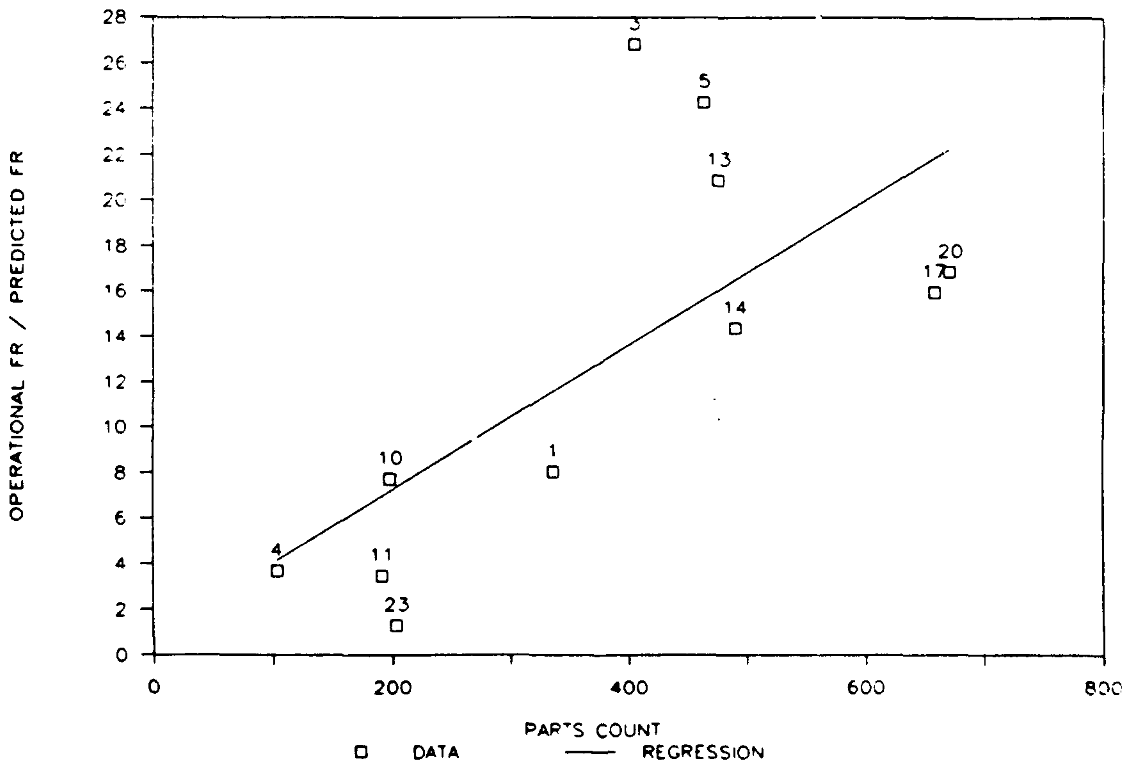


Figure 47.

<u>Power Supply Complexity vs Predicted Failure Rate Achieved (Grouped)</u>

The regression line passed the test for correlation.

Finally, the graph was plotted one more time (as Figure 48) with the power supplies for a given box grouped together to form one "power supply", ie., the high voltage units were thrown in with the low voltage units. This provided a good visual fit (regression line REG-ALL) with only one data point significantly out of the main group. However, due to the small sample size, the line REG-ALL failed the correlation test. With that data point #5 removed, the best fit of all was obtained with regression line REG-OTH. The line REG-OTH passed the correlation test. The equations of these lines are:

$$\text{REG-ALL,} \quad y = .02x - 1.29$$
$$\text{REG-OTH,} \quad y = .02x - 1.97$$

As illustrated in the last three graphs, the more complex power supplies have consistently proven to perform worse (with respect to their predicted failure rate) than more simple units.

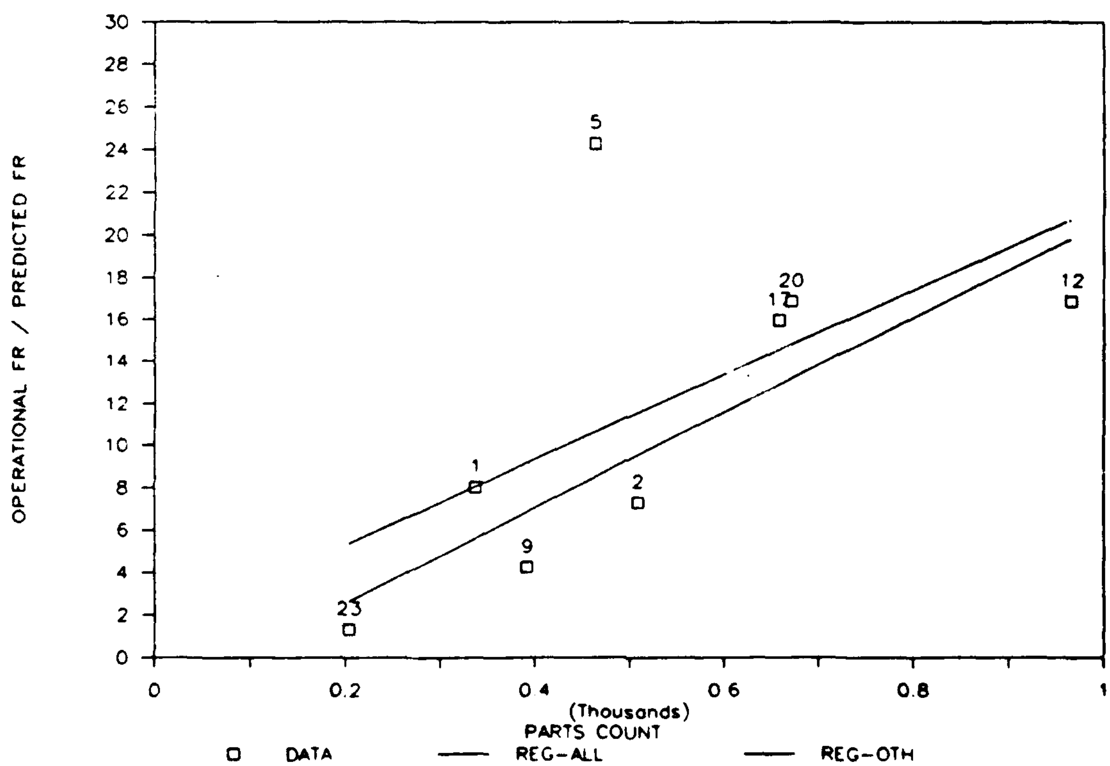


Figure 48.

Power Supply Complexity vs Predicted Failure Rate Achieved (WRA)

6.4 Protection Component Replacement vs % Total Parts are Protection Parts

To determine if protection circuity is deserving of having adjustment factors applied to the predicted failure rate of individual components, the following analyses were initiated to quantify the frequency at which the protective components failed with respect to their expected failure rate.

The first step of this process was to identify which parts on each power supply are associated with transient protection circuitry. For this purpose, all parts associated with sensing overvoltages or over-currents, comparing the voltages, clamping voltages or diverting currents are considered transient protection circuitry. The components necessary to bias and filter these protection components were also included. These components were identified from the power supply schematics.

The second step of the process was to determine how many of these parts actually were replaced during the time period in question. The H through Z records in the Navy's 3-M data base contain information on every part removed from the individual circuit cards. A detailed list of the replaced parts sorted by work unit code and part number was obtained from this data base. From this list, the number of replaced protection parts, identified by their reference designator, were tallied for each power supply.

Once the parts were identified and tallied, the ratio of protection components replaced to the total number of parts replaced for a given power supply was calculated (Ratio A). Next, the ratio of protection parts to total parts was calculated (Ratio B). These two ratios were then plotted (Ratio A on the y-axis and Ratio B on the x-axis) for all of the power supplies except the MDI high voltage power supply and the ARC-182 power supply (piece part information for these two units was not available from the 3-M data base). As Figure 49 illustrates, the protection components of all power supplies in the study, with the exception of two, were replaced at a lower rate than would be expected. The expected replacement rate is the replacement rate achieved when the percentage of replaced protection parts equals the percentage of protection parts in the circuit. The X-Y line is the expected replacement rate. The regression line for these data points is represented by the equation:

$$\text{REG,} \qquad y = .42x$$

This implies the actual failure rate of protection components is 42% of the expected failure rate. The test for correlation failed, however.

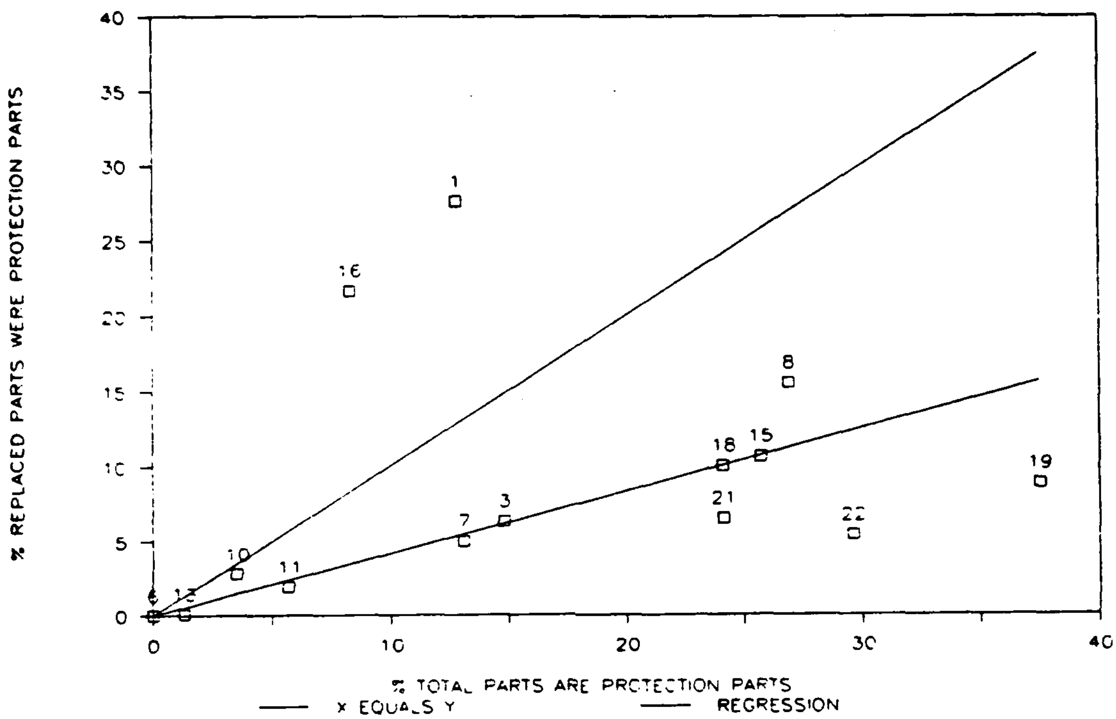


Figure 49. Protection Complexity vs Replaced Protection Parts (I)

Upon closer examination of the two data points (1 and 16), it was discovered that the values were being driven by one component in one case and a class of components in the other case. For data point 1, a very large percentage of the replaced protection components were fusistors - a resistor designed to fuse open at a given current level to protect output drivers on the power supply. In the other case (data point 16), the majority of protection component replacements were caused by two parallel resistors which were used as start-up current in-rush limiters. In both cases, the components are either being subjected to conditions far in excess of the design specification, being subjected to maintenance induced failures far above the norm, or have been misapplied or some combination of the above. Therefore, failures of these components were disregarded and the graph was replotted as Figure 50. With the fusistors and in-rush resistors removed, the two power supplies fell into line with the other power supplies. The regression line for this graph had the equation:

$$\text{REG,} \qquad y = .35x$$

This implies the protection components have a failure rate which is 35% of the expected failure rate of the protection components. The correlation test for this regression line passed.

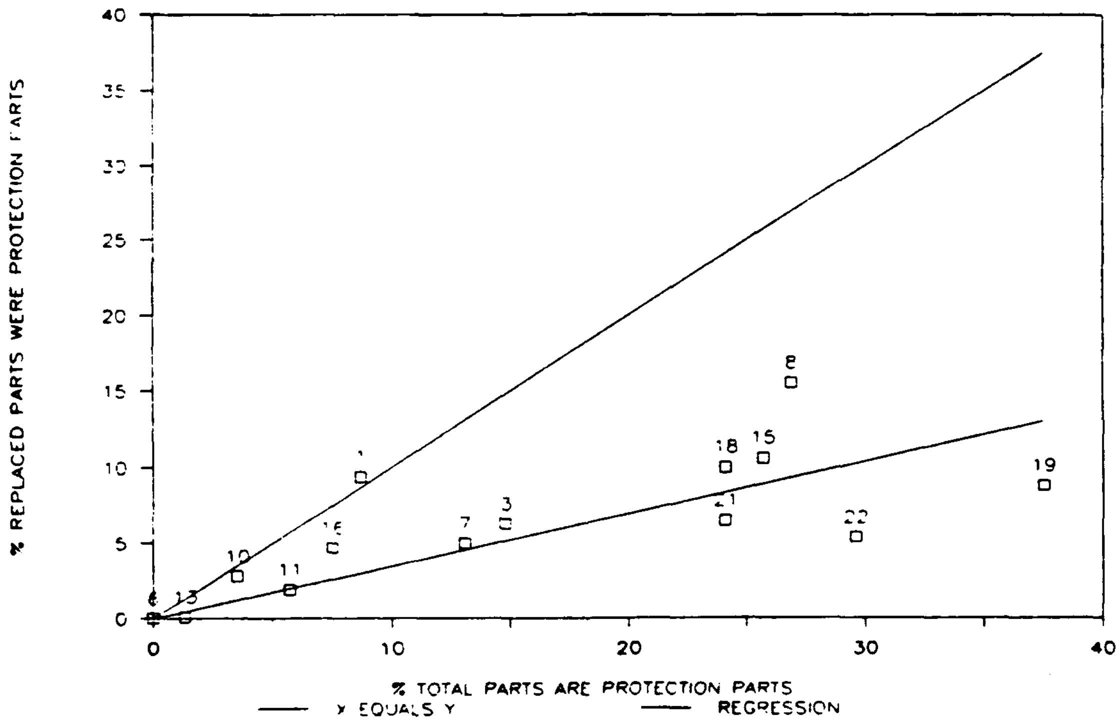


Figure 50. <u>Protection Complexity vs Replaced Protection Parts (II)</u>

6.5 <u>Protection Complexity vs Achieved Reliability</u>

This set of analyses was initiated to determine if the complexity of the protection circuity (as determined by the percent of total power supply parts which are related to protection circuitry) had any influence on the achieved failure rate of the power supply. The level of achieved failure rate would be expected to decline with increasingly complex protection strategies and subsequently increase with little or no protection.

Figure 51 was developed by comparing the achieved failure rates of all power supply SRAs (y-axis) to the protection complexity (x-axis). As illustrated, the data on the chart is very noisy and there appears to be zero correlation of achieved reliability to the amount of protection incorporated. A regression line was fit to the data, but the fit was very poor and it was not plotted. The equation of the regression line is:

$$\text{REG,} \qquad y = .06x + 15.52$$

Figure 52 is identical to 51 except that the SRAs were grouped together to eliminate some of the scatter. However, the data is still very noisy and, as expected, the correlation test failed. The regression line has the equation:

$$\text{REG,} \qquad y = .4x + 7.86$$

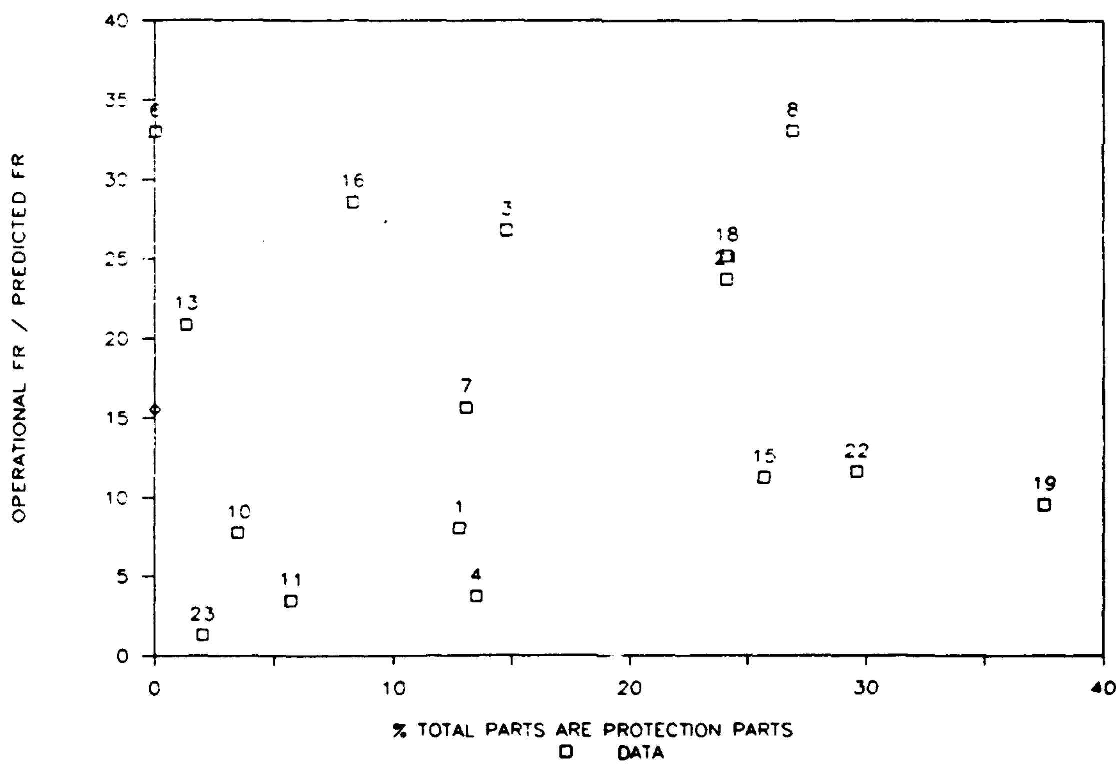


Figure 51. <u>Protection Complexity vs Predicted Failure Rate Achieved</u>

A different method of looking at the achieved reliability as a function of protection complexity was developed. Instead of determining the protection circuit complexity on the basis of parts count, the complexity was determined by the number of different types of protection offered. Overall, five types of protection were identified. They are input

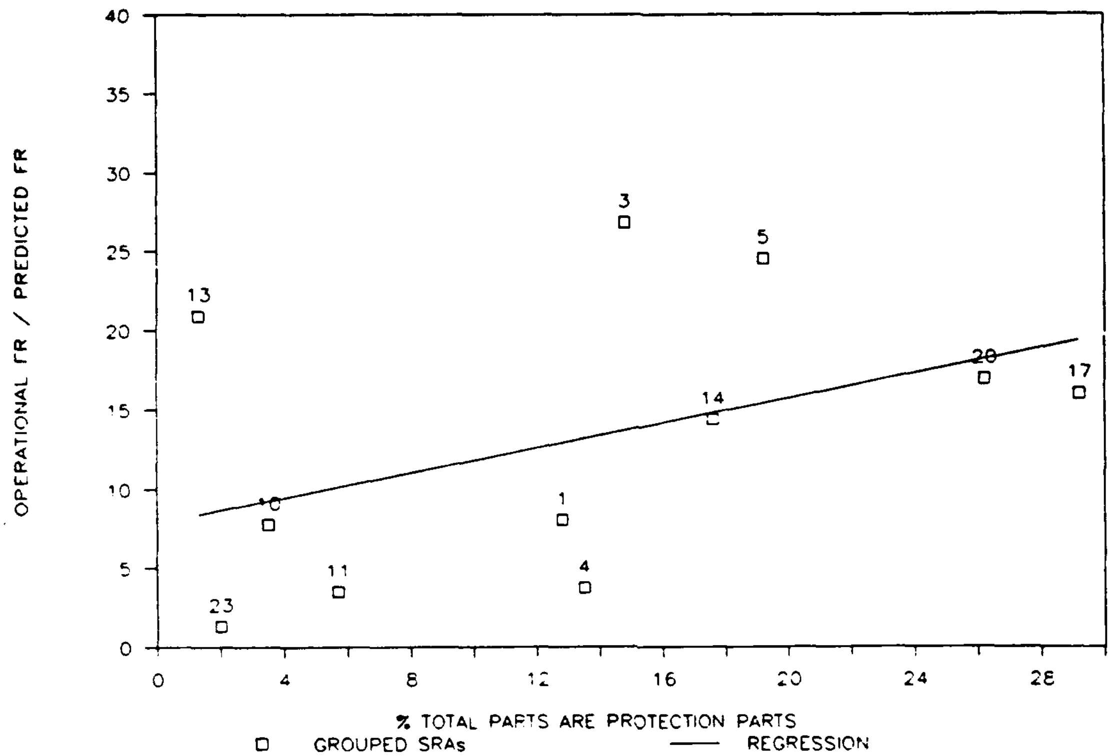


Figure 52.

Protection Complexity vs Predicted Failure Rate Achieved (Grouped)

overvoltage, output overvoltage, in-rush current limiting, normal current limiting and snubbing of transistors and inductors.

To start this analysis, each power supply was assessed to determine which types of protection they incorporate. Next, the power supplies were ranked according to the total number of protection types offered. The achieved failure rate of each power supply with the same number of protection types were summed together and an average value was obtained. The average values for each level of protection complexity were then plotted in Figure 53. For this plot, all of the power supply SRAs for a given electronic box were grouped together. This was done because, in many cases, one SRA of a given power supply would provide input protection while another SRA would provide the output protection. While the electronic boxes with three and five types of protection only represent a sample of one box, the general trend indicates (again) that electronic boxes with more complex protection perform more poorly than those with less. The regression line has the equation:

$$\text{REG,} \qquad y = 2.6x - 3.01$$

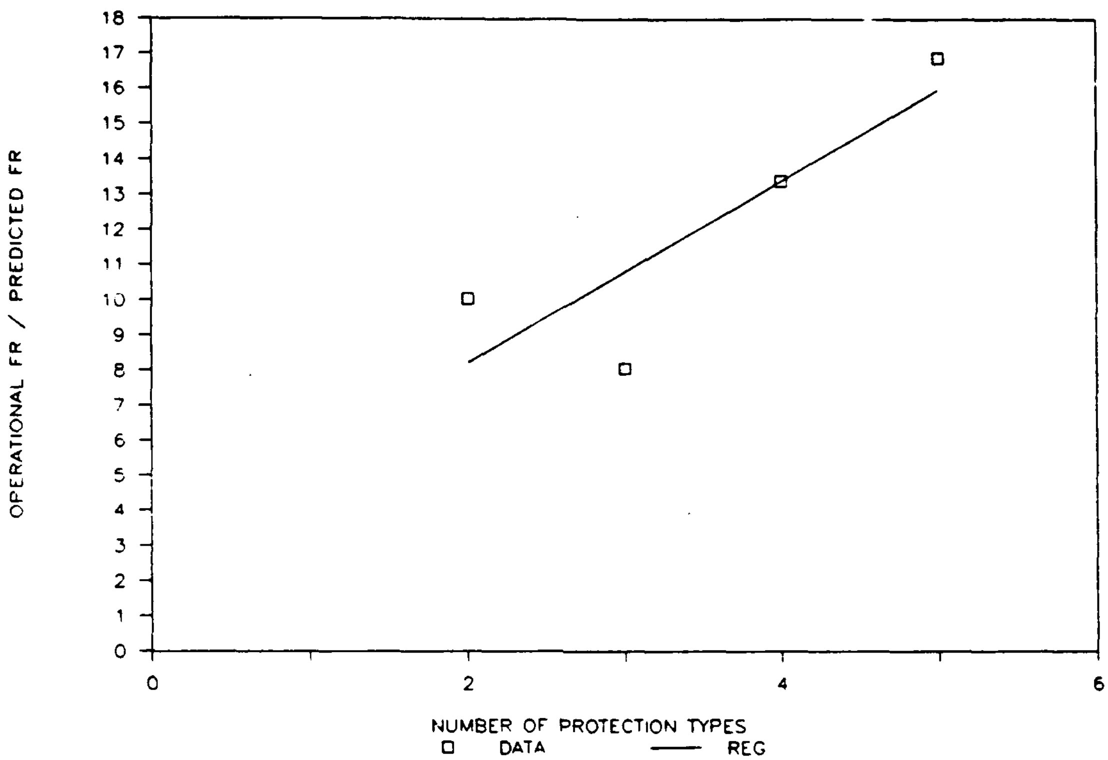


Figure 53. Number of Protection Types vs Predicted Failure Rate Achieved

A correlation analysis indicated no correlation due to a very small sample size.

Three additional charts were plotted using the same analyses as used for Figures 51 and 52 except that these charts were plotted based on the type of power supply they were, ie., a switching supply, a linear supply or a combination there of. The chart for the combination power supply is plotted as Figure 54, the linear type as Figure 55 and the switching type as Figure 56.

Figures 51 through 56 are not encouraging. Any firm conclusions would be difficult to make based on what appears in some cases to be random noise. However, if one were to use the regression lines as an indicator, five of the six plots indicated that increasing protection circuit complexity will cause the achieved failure rate to increase - the exact opposite result of

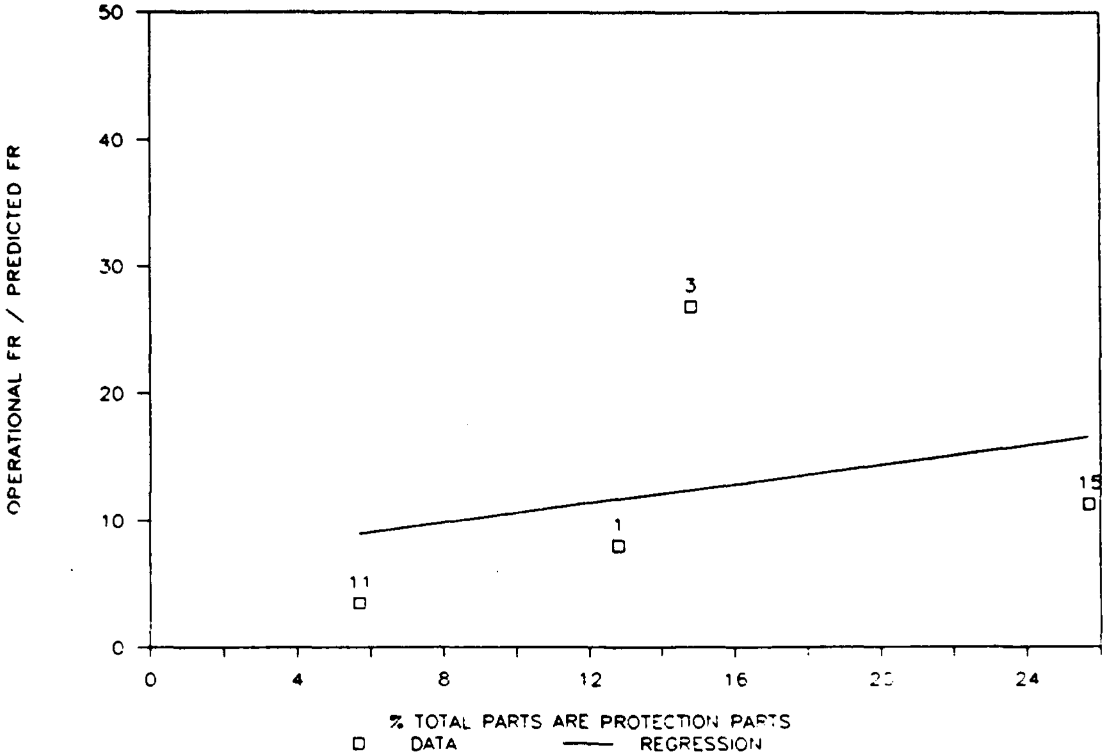


Figure 54. Protection Complexity vs Predicted Failure Rate Achieved (Combined Linear and Switching)

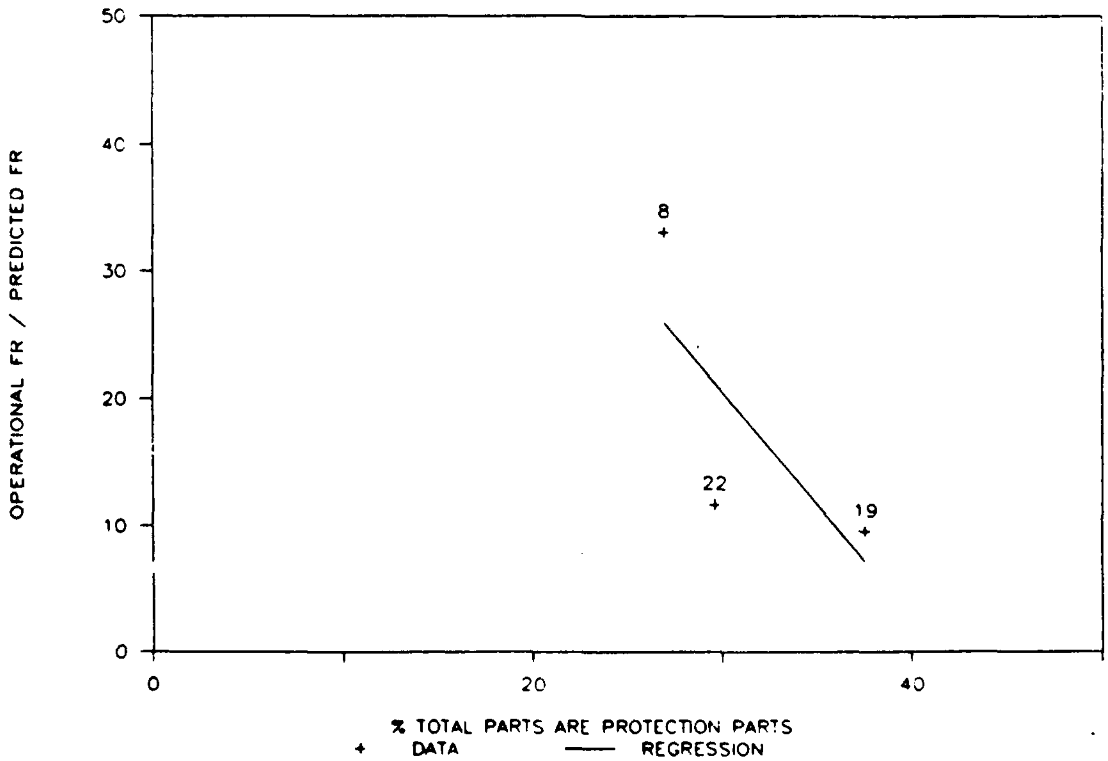


Figure 55. Protection Complexity vs Predicted Failure Rate Achieved (Linear)

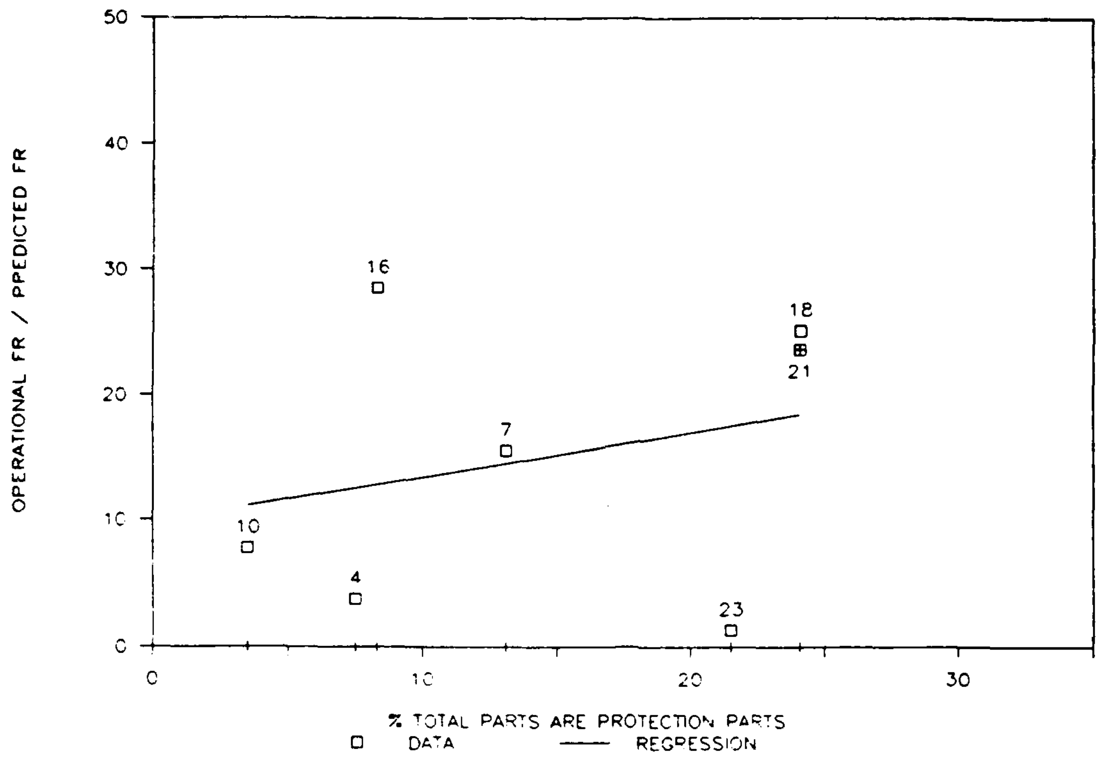


Figure 56. Protection Complexity vs Predicted Failure Rate Achieved (Switching)

what is expected! The follow on study we have proposed (in Chapter 7) will potentially explain this phenomena which is presently unexplainable with the information available. The one plot which did not show an increase had only three data points on which to base the regression and was discounted.

6.6 Power Supply Type vs Achieved Reliability

The last analysis performed compared the achieved failure rate (with respect to the predicted failure rate) with the power supply type, ie., switching regulator, linear regulator or a combination of the two. This analysis was performed on the individual SRAs of Table 4. The average value of the achieved failure rate of each type is illustrated in Figure 57. For the sample of this study, the supplies which were a combination of linear and switching regulators performed best with switching regulators coming in second. Linear regulators performed the worst, supporting the argument made by many (if not all) power supply designers. The relationship between the complexity of the various types of power supplies and the achieved failure rate can be seen in Figures 54 through 56.

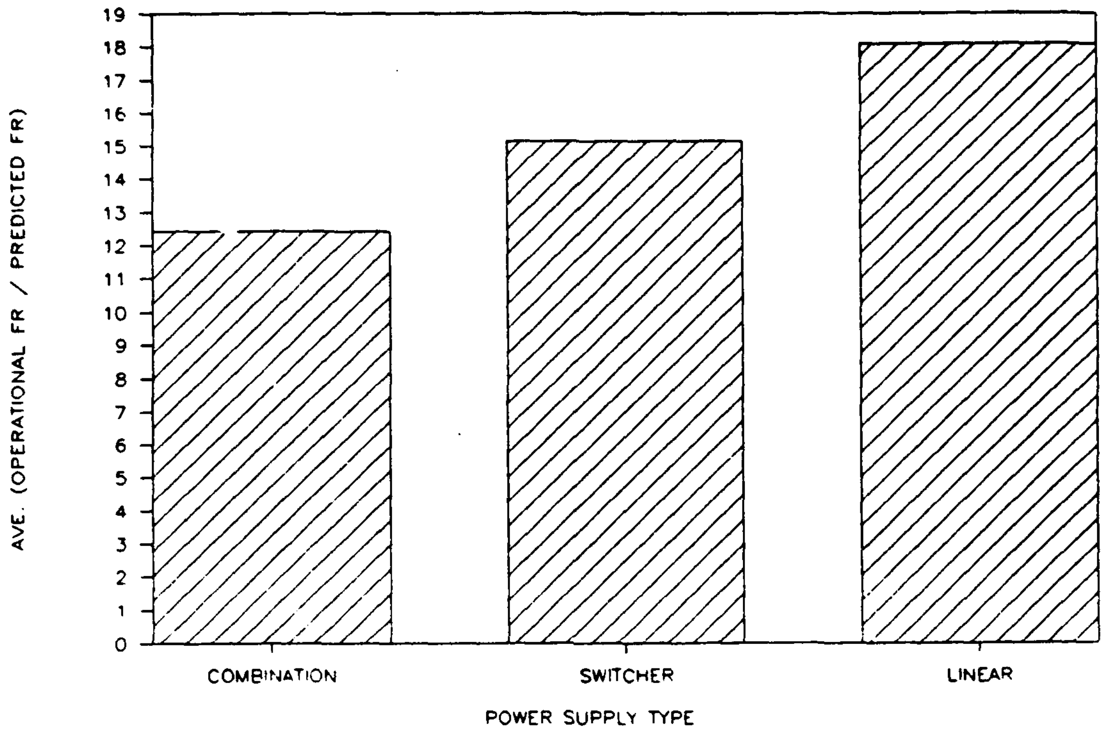


Figure 57. <u>Power Supply Type vs Predicted Failure Rate Achieved</u>

Chapter 7

Conclusions and Recommendations

7.0 Introduction

Task 7 of the statement of work required MCAIR to summarize the results of this effort and, if possible, develop adjustment factors to be applied to power supplies as a function of the transient protection incorporated.

7.1 Conclusions and Recommendations

The conclusions and recommendations are as follows:

1) Conclusion: Present specifications inadequately define the electrical environment power supplies must survive in.

   Recommendation: Procurement specifications must clearly define the transients that power supplies are expected to survive, ie., shorted outputs, voltage transients on the input or output, or in-rush current. The waveform, peak voltages and currents, duration, source impedance, transient application point and the performance requirements during the transient must be precisely defined. Without clear direction, the protection incorporated will vary widely from one manufacturer to another. Additionally, the procurement specification should require snubbing of switching transistors to protect them from transients which are undefinable until the design is complete and actual measurements are available.

2) Conclusion: Qualification and reliability testing does not adequately verify the ability of a power supply to survive electrical transients.

Recommendation: Qualification and reliability development test requirements should be expanded to include subjecting power supplies to specified transient conditions and verifying they can survive.

3) Conclusion: Purely analytical techniques are not adequate for derating and worst case analyses.

   Recommendation: Portions of these analyses must be confirmed with measured data. Specifically, dissipation of the power transistors during steady state operation, dissipation of the power transistors during transient conditions, peak voltages at the input and output during steady state and transient conditions, and peak in-rush currents must be measured and compared to the analytical values. The derating analyses should be updated to reflect these measured parameters and design changes should be made to rectify any problems.

4) Conclusion: There is a more than adequate selection of components, in both discrete and integrated circuits, available to the designer to implement transient protection simply and effectively.

   Recommendation: None

5) Conclusion: The data analyses indicate more complex protection schemes are associated with power supplies which perform progressively worse with respect to their predicted failure rate. However, the correlation tests for the regression lines all failed and adjustment factors could not be determined with confidence.

   Recommendation: It is difficult to believe that power supplies with more complex protection circuitry perform more poorly as a result of the circuitry. It is more likely a function of some other unidentified parameter. A controlled laboratory test is recommended, using a "standard" power supply to which varying levels of transient protection are attached and to which standard transients are applied to, would provide an unbiased evaluation of the effect protection complexity has on reliability.

6) Conclusion: The analyses also have shown more complex power supplies perform worse with respect to their predicted failure rates than less complex power supplies.

Recommendation: None

7) Conclusion: Transient protection parts fail at a much lower rate than the remaining components in a power supply.

Recommendation: According to the analyses of Chapter 6, the relationship between replacement rates of transient protection parts and the remaining electronics does correlate. The data suggests the predicted failure rate of transient protection components could be adjusted downward by 65%, or, the adjusted predicted failure rate P_{fra} is related to the original predicted failure rate P_{fro} by the following equation:

$$P_{fra} = .35P_{fro}$$

While this adjustment may not have a tremendous affect on the overall predicted failure rate of the power supply, it will help the designer whose design is exceeding its failure allocation. Viewed from a different perspective, the equation gives the designer two "free" components for every three protection components put in to the design.

8. Conclusion: The analyses confirmed the notion that power supplies fail more often than other assemblies within a piece of avionics.

Recommendation: None

9. Conclusion: Power supplies fail at a rate much higher than those rates obtained from the predictions.

Recommendation: Correlation analyses performed on the regression lines failed; therefore, adjustment factors can not be applied with confidence. However, the laboratory test mentioned in recommendation number 5 could be used to determine a reasonable adjustment factor to relate predictions to operational failure rates of power supplies.

10) Conclusion: Switching power supplies performed better than linear power supplies as compared to their predictions.

Recommendation: Switching power supplies are preferred. Use linear supplies only when necessary performance parameters require them.

7.2 Follow-on Study Proposal

A follow on study to address several areas is proposed. It would encompass several tasks which are:

1) Identify and characterize transients on military aircraft. This would be accomplished by instrumenting an aircraft electrical supply bus with a recorder to capture transient waveforms and durations. This would then be correlated with bus events to determine the characteristics of transients with respect to their sources. Additionally, typical power supply loads could also be characterized in order to provide optimum transient protection for the power supply outputs.

2) Model a "typical" power supply on an Analog Workstation. Incorporate various combinations of transient protection schemes into the supply and subject the model to simulated transients identified in the previous task. Taguchi experimental methods would then be used to choose the optimal transient protection schemes.

3) Build the modelled power supply with the optimum protection schemes and subject it to real transients (identified above) while verifying performance of the supply and the protection circuitry.

This follow on study will determine the most effective transient protection schemes for avionic power supplies.

Appendix A

Surveyed Companies

OPT Industries, Inc.
300 Red School Lane
Phillipsburg, NJ 08865

Pacific Electro Dynamics
11465 Willows Rd N.E.
Redmond, WA 98052

* Powercube Corp.
8 Suburban Park Drive
Billerica, MA 01821

Power Functions Eng., Inc.
3831 Cavialier
Garland, TX 75042

Power Supply Concepts, Inc.
33 County Rte. 1
Warwick, NY 10990

Power Jen, Inc.
486 Mercury
Sunnyvale, CA 94086

Rantec Power Systems
9401 Oso Ave.
Chatsworth, CA 91311

* RO Associates, Inc.
246 Caspian
Sunnyvale, CA 94089

Technipower/A Penril Co.
14 Commerce Drive
Danbury, CT 06810

Tri-Mag, Inc.
8210 W. Doe Ave.
Visalia, CA 93291

Trio Laboratories
#80 Duport Street
Plainview, NY 11803

Westcar Corp.
485-100 Alberta Way
Los Gatos, CA 95032

Acme Electronics
20 Water Street
Cuba, NY 14727

Arnold Magnetics Corp.
4000 Via Pescador
Camarillo, CA 93010

Abbott Transistor Labs
2727 South La Cienega
Los Angeles, CA 90034

Applied Power Conversion/Tech Dyn.
100 School Street
Bergenfield, NJ 07621

ATC Power Systems
472 Amherst St.
Nashua, NH 03063

CEAG Electric Corp.
1324 Motor Parkway
Hauppauge, NY 11788

Custom Power Systems, Inc.
33 Comac Loop
Ronkonkoma, NY 11779

EG and G Almond Instruments
1330 E. Cypress Street
Covina, CA 91724

Kepco, Inc.
131-38 Sanford Ave.
Flushing, NY 11352

Lamba Electronics
515 Broad Hollow Rd
Melville, NY 11747

Logitek
101 Christopher
Ronkonkoma, NY 11779

Modular Devices
Roned Rd, Brookhaven R&D Plaza
Shirley, NY 11967

* North Hills Electronics, Inc.
1 Alexander Place
Glen Cove, NY 11542

OECO Corp.
4607 S.E. International Way
Milwaukie, OR 97222

Abbott Technologies, Inc.
8203 Vineland Ave.
Burbank, CA 91352

Advance Power Systems
32111 Aurora Rd
Solon, OH 44139

AT&T Microelectronics
2 Oak Way
Berkeley Heights, NJ 07922

Conver, Inc.
916 W. Maude Ave.
Sunnyvale, CA 94086

Converter Concepts, Inc.
Industrial Parkway
Pardeeville, WI 53954

ORAM High Voltage
Klemp Rd
Dayton, TX 77535

Elpac Power Systems
3131 S. Standard Ave.
Santa Ana, CA 92705

General Electric Power Supply
1635 Broadway
Fort Wayne, IN 46802

Integrated Power Designs, Inc.
9C Princess Rd
Lawrencville, NJ 08648

Joule Power, Inc.
Summer Road, Joyce Industrial
Boxboro, MA 01719

Kaiser Systems, Inc.
126 Sohier Rd
Beverly, MA 01915

Mil Electronics
1 Mill Street
Dracut, MA 01826

Modern Power Conversion, Inc.
7100 Warden Ave., Unit #3
Markham, ONT, Canada L3R8B5

Modular Devices, Inc.
4115 Spencer
Torrance, CA 90503

* Marata Erie North America, Inc.
6338 Viscount Rd
Mississauga, ONT, Canada L4V183

NCR Power Systems
3200 Lake Emma Rd
Lake Mary, FL 32746

Onan Power/Electronics
4801 W. 81st St. Suite 114
Minneapolis, MN 55437

Panasonic Industrial Co.
Two Panasonic Way
Secaucus, NJ 07094

Power Electronics Corp.
30 Industrial Dr.
Londonderry, NH 03053

Power General Corp.
152 Will Drive
Canton, MA 02021

Power Systems, Inc.
45 Griffin Rd South
Bloomfield, CT 06002

Powertec, Inc.
20550 Nordhoff St.
Chatsworth, CA 91311

Shindengen America, Inc.
5999 New Wilke Rd
Rolling Meadows, IL 60008

Sola, Unit of General Signal, Inc.
1717 Busse Rd
Elk Grove, IL 60007

Spellman High Voltage Elec. Corp.
7 Fairchild Ave.
Plainview, NY 11803

Switching Power, Inc.
3601 Veterans Highway
Ronkonkoma, NY 11779

* Switching Systems International
500 Porter Way
Placentia, CA 92670

* Taltronics Corp.
404 Armour
Davidson, NC 28036

Toko America, Inc.
1250 Feehanville Dr.
Mt. Prospect, IL 60056

Tower Electronics
281 S. Commerce Circle
Fridley, MN 55432

Zenith Electronics Corp.
1000 Milwaukee Ave.
Glenview, IL 60025

* - Indicates respondents

Appendix B

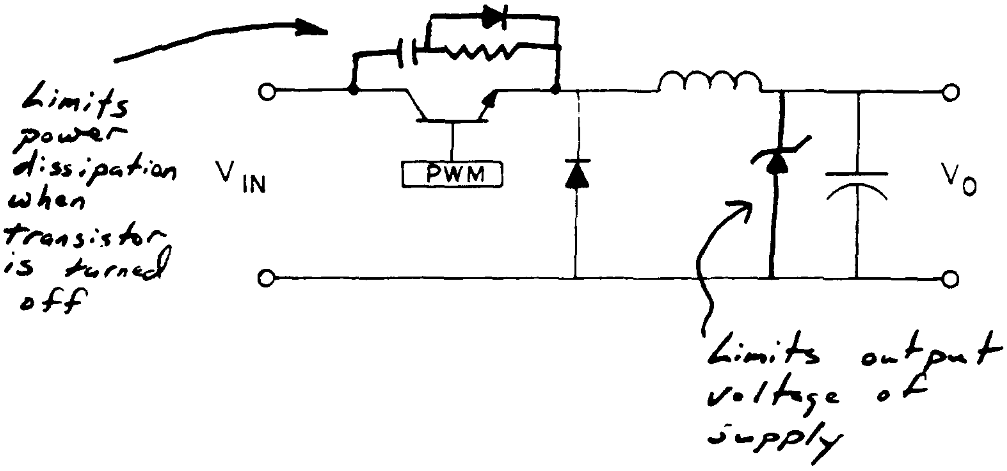
Survey And Survey Conclusions

Attachment (1)
Page 1

POWER SUPPLY QUESTIONNAIRE

1. What are the transient levels you normally design for? Please identify the peak voltage, peak current, volts per second rise, current per second rise and the transient duration. If a specification is used, please identify the source, i.e., MIL-STD-704, IEEE, etc.

2. Several different power supply rectifier and regulator topologies are illustrated in Figure 1. For those topologies utilized in your designs, please indicate where transient protection is incorporated, what type of transient it absorbs or diverts and what type of device(s) are used. Schematic representation is preferred, but block diagrams may be substituted if proprietary designs are involved. An example follows.



3. Please describe any transient protection properties which are inherent to your design.

POWER SUPPLY QUESTIONNAIRE

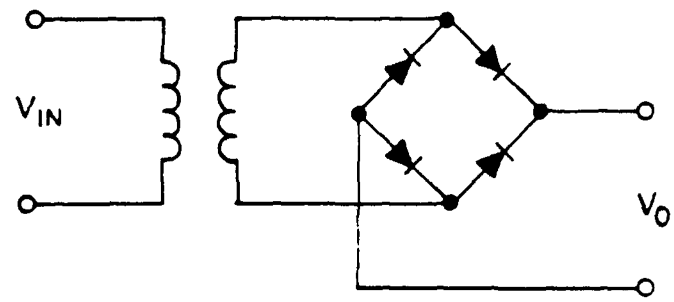
4. In your opinion, what percent of operational failures in protected and unprotected power supplies are a result of transient conditions?

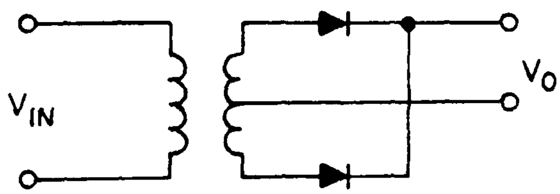
5. For power supplies with protective circuitry, approximate the percentage of operational failures that occur in the protective circuitry.

6. In your opinion, what are the trade-offs of added protection in terms of increased production costs, increased power dissipation and decreased operational failure rates?

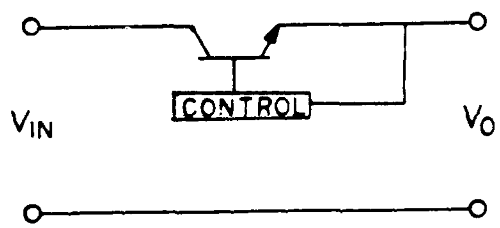
7. In your experiences, what are the real world limitations of the various protection schemes?

Rectifiers





Linear Regulator



Switching Regulators

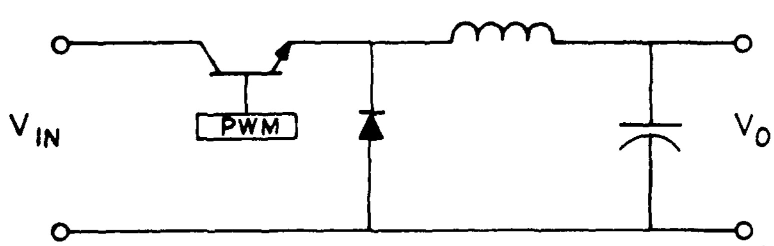


Figure 1

Switching Regulators (con't)

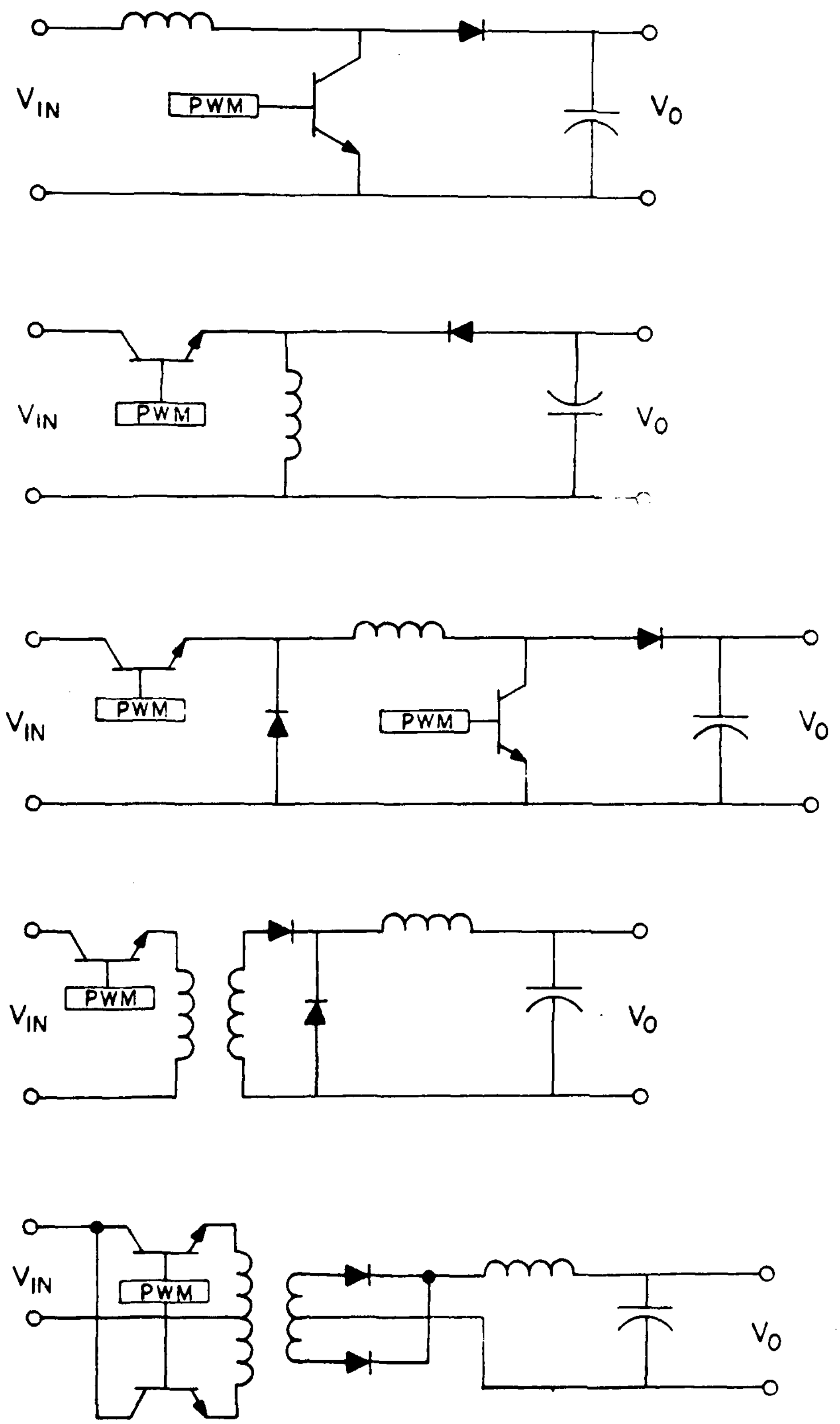


Figure 1

Survey Conclusions

The purpose of the first question of the survey was to gain insight into the transient levels the vendor designed their power supplies to withstand. Additionally, identification of the various power supply design specifications that are routinely used was requested. The input transients designed for was the only type identified by any of the vendors. The input transient levels and durations varied from one-half sine wave pulses of 2.5kV for 10 microseconds to 10kV rectangular pulses for one microsecond. It should be noted that levels of this magnitude are not found in any of the military specifications that are commonly referenced when specifying avionics equipment. The more common specifications identified were MIL-STD-704 (Aircraft Electrical Power Characteristics), DOD-STD-1399 (Interface Standard for Shipboard Systems) and IEEE-587 (IEEE Guide to Surge Voltages in Low Voltage AC Power Circuits).

The second question requested the vendors to identify the methods they use to protect their designs from internally and externally generated transients. Most vendors agreed that some type of protection was needed to suppress input overvoltage transients. The method used was generally either a Zener diode or metal oxide varistor placed across the input supply and return. Suppression of in-rush current during power up was also identified as a necessary protection scheme. Implementation examples included thermistors or resistors in series with the input line along with topologies which switch these devices out of the circuit when the supply is at steady state conditions. This eliminates the major disadvantage of in-rush current suppressors - power dissipation. Several vendors indicated some form of output overvoltage protection was necessary. A simple crowbar can provide protection for the load during power supply surges and for the power supply when the load or transmission line generates a surge. Additionally, a scheme which will also shut down the pass transistor during output overvoltage or overcurrent conditions is desirable.

The third question asked the vendors to describe any inherent voltage protection in their designs. The only form of inherent protection appears to be the input and output filters which are used to reduce output ripple and to keep noise generated in the power supply off of the power bus.

Unfortunately, the filters directly contribute to an increase in in-rush current.

The fourth question was asked in an attempt to get the vendor's opinion of the extent of transient induced power supply failures. The answers fell into two widely separated categories. The majority of vendors believed very few failures were a result of transient conditions (0-15%). One vendor had a totally different opinion, however, indicating 75-95% of power supply failures were a result of transients. The response of the first group brings two possible scenarios to mind. Either transients are not a problem and we should not waste time and money designing for them or transient protection schemes are very effective in protecting power supplies from the transients to which they are subjected.

The fifth question was an attempt to quantify the reliability of the actual transient protection devices. The vendors were asked to approximate the percentage of power supply failures caused be transient protection devices. The vendors appeared to be in total agreement on this issue. All suggested less than 2% of failures were a result of protection devices.

The sixth question asked the vendors to assess the trade-offs of transient protection in terms of added cost, increased power dissipation and increased operational reliability. The main point emphasized was the notion of lowest life cycle cost. If transient protection is necessary to protect an expensive power supply or load, then use it. Otherwise, protection is a waste of energy and resources.

The final question asked what the real world limitations of transient protection were. There was the expected response dealing with the increased power dissipation of protection devices, but the most interesting response dealt with unspecified transient source characteristics. In particular, the source impedance is generally not specified, and when it is, it is unrealistic. This is a problem which was repeated over and over in the literature. Without this information, it is impossible to design an optimum protection scheme.

Appendix C

Bibliography

Bibliography

1. Protection of Integrated Circuits from Electrical Transients; Clarkson College of Technology, Potsdam, NY; June 1982
This report summarizes the threat to integrated circuits from electrical transients and different approaches to protect circuits from transients.

2. Designing Power Line Transient Protection Circuits; NM Jacobus, Jr.; COMSAT Laboratories, Clarsburg, MD; Proceedings of Powercon 11; 1984
This paper presents a method of designing a transient protection circuit that will perform over the full spectrum of expected transients.

3. Continuation of Surge Life of Transient Voltage Suppressor, NASA-Cr-150499; General Semiconductor Industries, Inc.; O.Melville Clark; May 1977
This report documents the efforts expended in testing, analyzing and development of the definition of the life of the TRANZORB family of voltage suppressors.

4. Transient Voltage Suppressors Design and Selection Guide; Unitrode Corporation; 1987
Discusses transient models, both internally and externally generated. Includes criteria for selecting an appropriate voltage suppressor, application and comparisons of various voltage suppression techniques.

5. Mine Power Systems Research - Transients and Enclosures; Information Circular 8802; Staff - Mining Research, Bureau of Mines; 1982
Discusses transients and methods of controlling transients as applicable to mine power distribution systems.

6. Motorola Linear/Switchmode Voltage Regulator Handbook; Motorola, Inc.; 1987. A handbook on power supply design using Motorola components.

7. Limiting In-rush Current to a Switching Power Supply Improves Reliability, Efficiency; Roger Adair, Unitrode Corporation; 1980. Discusses several methods which can be used to limit the in-rush current of power supplies during turn-on.

8. General Characteristics of Varistors, Application Data; Midwest Components, Inc.; 1989
Discusses the general properties and application of varistors as transient protection devices.

9. Microelectronics Digital and Analog Circuits and Systems; Jacob Millman, McGraw-Hill Book Company; 1979
A electrical engineering textbook on fundamental theory and application of microelectronics.

10. McGraw-Hill Encyclopedia of Science & Technology; McGraw-Hill Book Company; 1984
Explanations as applicable to the engineering field. Includes theory of operation, application, definition, etc.

11. Electronics Engineer's Handbook; Donald Fink, Donald Christiansen; McGraw-Hill Book Company; 1989
A collection of short explanations of engineering terms, concepts, equations, technology, etc. as applicable to electronics engineering.

12. RCA Surgector Application Guide
Discusses the properties and application of the RCA SURGECTOR transient voltage suppressor, a monolithic device which integrates a Zener diode with an SCR.

13. Transient Voltage Suppression; General Electric, 1986.
Discusses transient sources, protection devices, applications to power

supplies, and testing requirements of protection circuitry.

14. General Characteristics of Thermistors - Application Data; Midwest Components, Inc.; 1989
Discusses the general properties and applications of positive and negative coefficient thermistors as transient protection devices.

15. Unitrode Switching Regulated Power Supply Design Seminar Manual; Unitrode Corporation; 1984
Discusses various topologies including switching and resonant power supplies. Covers the effects of leakage inductance and new products advances in power supply control.

16. Silicon General Component Data Book; Silicon General; 1988
Data book for components manufactured by Silicon General.

17. Grayhill Engineer, Volume 23 Number 2; Grayhill, Inc.
Discusses implementation of crowbar circuitry in digital circuits.

18. The Output Supervisory Circuit - A New Analog LSI Circuit for Power Supply Control; RA Mammano, Silicon General, Inc.
Describes a monolithic integrated circuit which contains all the functions necessary to monitor and control the output of a power supply system.

19. MMCC DIA Surge Absorber - Application Book; Mitsubishi Mining & Cement Co., Ltd.; 1988
Application and product description handbook for MMCC's gas discharge tubes.

20. Metal Oxide Varistors for Surge Voltage Protection - Application Book; Siemens Components Inc.; 1989
Application and product description handbook for Siemens' metal oxide varistors.

21. Siemens SVP Surge Voltage Protectors - Applications Book; Siemens Components, Inc.; 1989

Application and product description handbook for Siemens' gas discharge tubes.

22. General Semiconductor Component Data Book; General Semiconductor Industries, Inc.; 1987
The component data book for General Semiconductor.

23. Power Supply Voltage Transient Analysis and Protection; Richard D. Winters, General Semiconductor Industries, Inc.; Powercon III Proceedings; 1976
Explains and defines transients and transient sources. Discusses methods of suppressing transients with TRANZORBs. Details the process for selecting the proper TRANZORB for the application.

24. Methods for Utilizing High-Speed Switching Transistors in High Energy Switching Environments: William R. Skanadore, General Semiconductor Industries, Inc.; Proceedings of Powercon IV; 1977
Presents insight into the failure mechanisms associated with high speed switching transistors and discusses appropriate action to safeguard against these failures.

25. Switching & Linear Power Supplies, Power Converter Design; Abraham Pressman; Hayden Book Co.; 1977
A textbook on basic design practices of power supplies including linear and switching regulators.

26. Power Integrated Circuit Makes Board Level Overvoltage and Overtemperature Protection Simple and Inexpensive: D. Zaremba & J. Mansmann, Motorola Inc.; PCIM 1985
Discusses the overvoltage controller (SMARTPOWER) manufactured by Motorola. This monolithic device monitors for overvoltage and over temperature conditions. A self contained SCR is fired when an overvoltage exists.

27. Characterizing Overvoltage Transient Suppressors; Al Pshaenich, Motorola Power Products Division; Powerconversion International,

July 1985
Article discusses methods of implementing transient test circuits and the advantages and disadvantages of various transient protection devices.

28. Start Up Transients in Switching Regulators and Input Filters; A.P. Brokaw, Analog Devices, Inc.; Solid State Power Conversion, 9/76. Discusses start-up transients and methods of protecting the power supply and load from them. It also covers simple analytical methods to determine the magnitude of these transients.

29. Applying AVIP to High Voltage Power Supply Designs; W. Dunbar, J. Rugama; AFTWAL TR-88-4143.
The paper discusses methods to apply AVIP principles to high voltage power supplies. Discusses common failure mechanisms in HVPSs and what can be done to eliminate them. Includes life degradation curves for insulation resistance based on temperature, frequency and voltage.

30. Power Supplies: Make the Specs Work for You; C. Alleva, Power Systems, Inc.
Discusses proper specification writing and how to test for functional performance requirements.

31. Inside the "Black Box" - A Look at Power Supply Design; J. Till; Electronic Design, July 14, 1988.
Basic article describing various power supply architectures and their respective advantages.

32. Designer's Guide to Circuit Protectors; M. J. Coyle, MCG ELectronics. Provides a comparison between the various attributes of transient protection devices.

33. Transient Voltage Suppression Adds to Automobile Reliability; S. Korn, General Electric Co.; Design News, 10/85.
Discusses the application of transient suppression circuitry to cars.

34. The Output Supervisory Circuit - A New Analog LSI CIrcuit for Power

Supply Control; R. Mammano, Silicon General, Inc.
Discusses the SG1543 power supply supervisory microcircuit developed by Silicon General.

35. The Interpretation of Electrical Overstress in Power Transisitors; T. Lee, Motorola, Inc.
Discusses the failure mechanisms of power transistors. Investigates methods of identifying the cause of the failure via failure analysis.

36. Characterizing the SCR for Crowbar Applications; A. Pshaenich, Motorola Semiconductor Products Inc.; Application Note AN-789, 1978.
Provides detailed instructions for the application of SCRs in crowbar ' cuitry. Provides design guidelines with respect to energy dissipation, current capacity, gate drive and SCR life testing.

37. Hardening Power Supplies to Line Voltage Transients; B. Roehr, General Semiconductor Industries, Inc. Discusses methods to integrate the rectifier and input filter capacitors with transient suppressors into an efficient protection scheme.

38. How to Prevent Circuit Zapping; R. Antinone, BDM Corp.; IEEE Spectrum, 4/87. Describes and defines transients and their sources. Provides explanations of the failure mechanisms of semiconductors.

39. Optimizing Line In-rush Design in Off-Line Converters; W. Hirschberg, ACDC Electronics Division of Emerson Electric Co.
Discusses the problem of in-rush current during power up. Techniques for limiting this current are presented.

40. Transient Suppressors Compared; General Electric Co.; Solid State Power Conversion, 3/79.
Compares the V-I characteristics of various voltage suppressors. Also discusses the change in standby power of suppression devices as a function of applied steady state voltage.

41. Power Integrated Circuit Makes Board Level Overvoltage and Overtemperature Protection Simple and Inexpensive; D. Zaremba, J.

Mansmann, Motorola Inc.; PCIM, 10/85.
Discusses the application of Motorola's SMARTPOWER protection device.

42. Doing Surge Tests Properly; P.Richman, KeyTek Instrument Corp.; EMC Technology, 5/89.
Delineates the proper methods of testing equipment for immunity to transients. Discusses the common variations in testing approaches which supposedly have the same goal in mind.

43. Navy Power Supply Reliability - Design and Manufacturing Guidelines; NAVMAT P-4855, Department of the Navy; January 1989.

44. Probability and Statistics for Engineers; Irwin Miller, Opinion Research Corporation & John Freund, Arizona State University; Prentice-Hall, Inc.; pp. 322 - 328; 1985.
A probability and statistics textbook.

Appendix D

Equipment Information

ID#	Nomenclature	Manufacturer	Number per Aircraft	Part Count (each)	Predicted MTBF (hours)	Field MTBF (hours)	PCB Removals	Soft Start	Input Over Voltage	Output Over Voltage	Current Limit	Snubbing	Power Supply Type*
	Flight Control Computer	General Electric	2		1315	853	1765						
	1. Low Voltage Supply		4	337	38485	4785	629			X	X	X	C
	ARC 182 Transceiver	Rockwell	2		1427	1310	871						
	23. Low Voltage Supply		2	204	24469	18710	61			X	X		S
	Inertial Navigation Set	Litton	1		1926	408	1648						
5.	6. Rectifier/Filter		1	31	335796	10177	66						
	7. DC-DC Converter		1	199	150240	9595	70				X		S
	8. Sequence Monitor		1	234	277778	8396	80			X			L
	Horizontal Situation Display	Bendix	1		1243	251	3157						
9.	10. High Voltage Supply		1	199	38456	4956	160			X	X		S
	11. Low Voltage Supply		1	192	8294	2374	334			X	X		C
	Radar Transmitter	Hughes	1		1165	277	2209						
12.	13. High Voltage Supply		1	476	16625	797	767			X	X		T.
14.	15. Power Converter		1	261	12708	1127	542	X	X	X	X	X	C
	16. Switching Regulator		1	229	58241	2037	300	X			X	X	S
	Target Data Processor	Hughes	1		461	441	1386						
17.	19. Linear Regulator		1	248	23283	2435	251			X	X		L
	18. DC-DC Converter		1	410	33501	1328	460	X		X	X	X	S
	Computer/Power Supply	Hughes	1		818	541	1129						
20.	21. DC-DC Converter		1	411	38760	1634	374	X		X	X	X	S
	22. Linear Regulator		1	260	29824	2568	238			X	X		L
	Multipurpose Display Indicator	Kaiser	2		1898	367	4313						
2.	3. Low Voltage Supply		2	405	82186	3063	516	X	X	X	X		C
	4. High Voltage Supply		2	104	15000	4022	393		X	X			S

* C- Combination of linear, switching, or transformer coupled; L - Linear; S - Switching; T - Transformer coupled

Notes

1) PCB removals are a subset of box level removals

2) Removals include only maintenance actions considered failures by the Navy 3-M logic.

3) Flight hours for this data set equals 505022 hours.

Table 6. Equipment Information

MISSION

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